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FINAL PROJECT REPORT**

**SUMMARY OF RECENT WIND  
INTEGRATION STUDIES**

**Experience from 2007-2010**

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**PRIMARY AUTHOR(S):**

Phillip de Mello  
C.P. (Case) van Dam

California Wind Energy Collaborative  
University of California, Davis

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**Prepared for:**

**California Energy Commission**

Prab Sethi  
**Contract Manager**

Linda Speigel  
**Office Manager**  
**Energy Generation Research Office**

Laurie ten Hope  
**Deputy Director**  
**ENERGY RESEARCH AND DEVELOPMENT DIVISION**

Robert P. Oglesby  
**Executive Director**

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## PREFACE

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## ABSTRACT

This study reviewed and summarized wind integration studies focused on the United States from 2007 through 2010. Wind integration studies were performed to assess the operational requirements for incorporating large amounts of wind into the power grid. A variety of methods for assessing wind impacts were examined and compared. Integration studies showed that the reliable operation of a power system would continue to be possible with increased wind energy.

The results of the studies that were surveyed indicated that wind generation will affect the power grid in a number of ways. Estimated costs associated with wind integration varied widely among studies. Wind will introduce additional variability and uncertainty into the power grid. A variety of mitigation measures were suggested for dealing with the variables associated with wind generation. Reliable wind forecasting was critical to successful operations involving large amounts of wind generation. Several areas for additional study with respect to wind integration were recommended. This study benefitted California ratepayers by providing information on a key source of clean renewable energy with the potential for significant human health benefits, environmental benefits, and cost savings.

**Keywords:** Wind integration, wind generation, wind generation variability, grid management, renewable energy, power system

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# **EXECUTIVE SUMMARY**

## **Introduction**

Wind generation is playing an increasing role in meeting the world's energy needs. In the United States this growth has been driven by renewable portfolio standards, production tax credits, adequate wind resource, and a low relative cost. California's Renewable Portfolio Standard requires that utilities and other electric service providers meet 33 percent of their load requirements with renewable resources by 2020. More than 40 gigawatts (GW) of wind capacity have been installed in the United States. It is important to understand the effects that renewable energy will have on the power grid as renewable energy penetrations increase.

## **Project Purpose**

The goal of this study was to review many of the recent wind integration studies in the United States. Integration studies were performed for areas that are likely to see a large increase in wind power. These reports provided insight into how the power grid will perform with large amounts of wind generation. Researchers performed wind integration studies to evaluate several factors including anticipated costs, reliability issues, and any operating changes associated with incorporating wind generation.

Researchers surveyed the literature on integrating wind power in the power grid from recent years. They focused on studies released between 2007 and 2010 that addressed wind generation factors within the United States, as shown in Table 1.

**Table 1: List of Integration Studies**

<b>Study Name</b>	<b>Prepared by</b>	<b>Date</b>	<b>Shortened Name<sup>1</sup></b>
Operational Impacts of Integrating Wind Generation into Idaho Power's Existing Resource Portfolio [1,2]	Enernex	Feb-07	Idaho
Avista Corporation Wind Integration Study [3]	Enernex	Mar-07	Avista
Intermittency Analysis Project: Final Report [4,5,6]	GE	Jul-07	CEC IAP
Arizona Public Service Wind Integration Cost Impact Study [7]	Northern Arizona University	Sep-07	Arizona
Integration of Renewable Resources [8]	California ISO	Nov-07	CAISO
Analysis of Wind Generation Impact on ERCOT Ancillary Service Requirements [9]	GE	Mar-08	ERCOT
20% Wind Energy by 2030 [10]	NREL	Jul-08	20% by 2030
Montana Wind Power Variability Study [11]	Genivar	Sep-08	Montana
Eastern Wind Integration and Transmission Study [12]	Enernex	Jan-10	EWITS
Nebraska Statewide Wind Integration Study [13]	Enernex	Mar-10	Nebraska
Western Wind and Solar Integration Study [14]	GE	May-10	WWSIS

This study described the operation of the power system and how wind generation will fit into that framework. System operators need to continuously manage the supply and demand of power systems. Power systems are complex and controlling them involves using many planning and operating processes. All of these procedures were designed for systems with uncertain load and controllable generation. The addition of wind generation changes that balance toward more uncertain generation and therefore warranted study. Wind turbine generators and their operating characteristics are an important part of wind integration studies. Wind generation is an intermittent, variable, and uncertain generating resource, in sharp contrast to conventional generation, which is available as needed and is controllable. System

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<sup>1</sup> The shortened name is an abbreviation for the study that is used throughout this paper to refer to the studies.

operators worry that the characteristics of wind generation will present control problems within the system. The integration of large amounts of wind power will likely require some changes to standard procedure. It is important to understand what these differences are likely to be and what needs to be done to implement the necessary changes.

## Project Results

Current wind integration studies tended to focus on the operational issues of the power system using increasing wind generation. The physical issues and impacts were generally handled in less detail. Wind integration studies include a variety of analyses to better understand wind generation on its own as well the interaction of wind and the power grid. The methods that studies used to analyze the wind played an important role in the results. There are a few common methods that were employed in many studies, but even with these common tools there were a number of assumptions and parameters that influenced the results. Understanding the differences between methods was very important when trying to compare results between studies.

Wind integration studies need to define the conditions that they are studying. The studies were based upon the current amounts of wind generation on the system and researchers also studied future periods with increased generation. Wind integration studies created different scenarios for how the power system will look in the future, often with differing amounts of wind generation. It was also common for studies to consider cases with similar amounts of wind generation but spread out into different areas. Creating the most realistic scenarios possible was fundamental to obtaining realistic results.

Statistical analysis was often the first set of analyses applied in wind integration studies. The statistical methods tended to study either the wind generation profile or the load minus the wind generation profile. In both cases studies analyzed the data to determine the magnitude, frequency, and duration of changes. This information was then used to define a new baseline of the power system to understand how much the control is expected to change. Statistical methods were also useful for developing an understanding of wind generation behavior by time-of-day, season, and other factors that were relevant to operation.

Researchers performed operational analyses to investigate possible operating changes with increased wind energy. Operational studies attempted to model the system operations of the region being studied. This led to a divergence among the models because there were different operating practices to consider. The most common type of operational analysis used a production cost simulation model on the various forecast scenarios. Production cost models simulated the operation of the power grid by matching supply and demand and calculating power flows across the network. Even though the techniques were similar, there were many parameters that can differ in application and these differences affected the results.

Researchers found that the variability that wind introduced into power systems was generally less than the variability that was present due to load. That does not mean that the wind does not add additional variability. The net load, or load minus wind generation, is what system operators need to be able to accommodate. The variability of the net load is less than the

variability of the load plus the variability of the wind. This increase in variability will require system operators to take more and larger control actions to keep the system balanced. The uncertainty of wind in the power system was the largest concern. The variability introduced was generally manageable but it was made worse by the uncertainty. Uncertainty made it much more difficult to plan generation schedules in an optimal way.

The variability and uncertainty of wind generation will cause operators to increase the amount of ancillary services they procure to keep the system balanced. Ancillary services are a subset of a group of services that are necessary to maintain operation of the power grid. They are used to maintain short-term balance of the system and to recover from unexpected outages. Ancillary services included operating, contingency, and regulating reserves. The regulation reserve was the most affected because it was primarily charged with managing short-term fluctuations. The amount of additional regulation that systems will need to procure varied greatly between studies. Regulation needs increased with higher penetrations of wind generation. It was important for system operators to quantify the regulation needs to ensure that the system would have the capability to provide it.

Determining the costs of wind integration was one of the main goals of many studies. These studies used a wide range of methods and assumptions to determine costs. There were many possible ways that wind generation could affect power system costs. Wind generation can affect energy costs, ancillary service costs, unit commitment costs, congestion costs, uplift costs, and transmission costs, among others. Direct comparisons of wind integration costs were difficult because different studies chose to include different factors when making cost calculations. Studies found wind can reduce energy cost by displacing more expensive generation. These savings may be offset by higher costs introduced from other elements such as increased ancillary service costs. The extra cost estimates ranged from \$0/megawatt hour (MWh) to \$9.35/MWh.

Wind generation could play an important role in helping to reduce emissions resulting from electric power generation. Large amounts of wind power could displace electricity normally produced from fossil fuel-fired generators. Wind generation combined with a carbon tax could reduce emissions substantially. Studies have shown that carbon dioxide reductions could be as large as 45 percent under certain conditions.

The most important conclusion was universal among wind integration studies: reliable operation of the power grid will be possible with the wind penetrations considered. The fact that reliable operation will be possible suggested that wind energy will be able to play an important role in meeting future energy needs. Managing increased wind generation will require many changes to current operating procedures. The success of wind generation may ultimately rely on the policies and practices of the system operators.

Various studies recommended many ways to successfully integrate wind power into the system. The recommendations fell into three basic categories: reducing uncertainty, increasing flexibility, and increasing diversity.

**Reducing the uncertainty** of wind generation was the primary method recommended to facilitate integration. Forecasting for wind generation was the most important strategy for integrating wind into the power grid. Forecasting reduced the uncertainty of wind directly and could potentially result in very large savings for the power system. Forecasts would be designed for each area to fit current operating practices. These forecasts could provide insight into the expected level of generation and variability that wind power will introduce into the system, which will give operators the ability to make adjustments or procure extra capacity as needed.

**Increasing the flexibility** of the power grid was the second strategy for managing wind integration. Increasing the amount of ancillary services, specifically regulation, was a common tactic to increase the system's flexibility. This would literally increase the amount of capacity that is tasked with following variations between the load and generation. Other methods of increasing flexibility were also suggested but were more dependent on system and operating practices.

**Increasing diversity** was the third strategy for optimally managing integration. Diversity can be increased in a number of ways. Building wind generation in different resource areas was one way to increase diversity. Constructing sufficient transmission to ensure wind power can be moved to where it is needed was another. Combining control areas or increasing the cooperation between areas was another viable strategy. Increasing cooperation would involve increased scheduling frequency across entities and sharing renewable energy data.

Adopting these recommendations is necessary for successful wind power integration. Further study of wind power integration will be important as more capacity is installed, as better information becomes available, and as better tools to analyze wind are developed. Wind integration studies are also generally targeted to address certain goals. There may be many issues of interest that fall outside those goals and that need to be analyzed in further studies. Current study results suggested that looking at integration in more detail using sub-hourly studies or extreme weather condition studies should be recommended. Studies also recommended looking at wind integration with different future conditions that may be driven by new technology development, environmental regulations, and operating practice changes.

### **Project Benefits**

This study benefitted California ratepayers by providing information on a key source of clean renewable energy with the potential for significant human health benefits, environmental benefits, and cost savings.

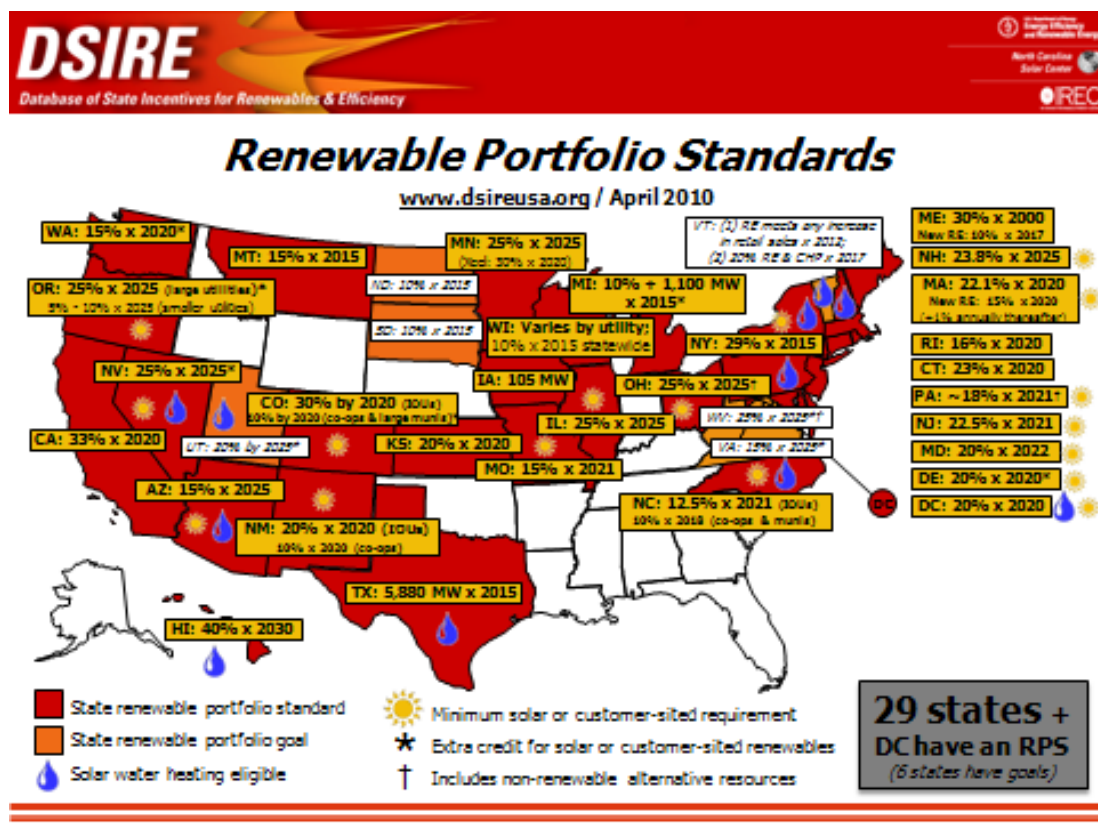


# CHAPTER 1: Introduction

There has been increasing interest in wind energy throughout the world including the United States. Many states have enacted renewable portfolio standards (RPS) requiring certain amounts of electricity from renewable resources,

Figure 1. Projections over the next several years also indicate there will be significant increases in wind power generation throughout the United States. Wind energy is an intermittent variable resource and can present some unique characteristics in the power system. With larger amounts of wind power producing electricity there is significant interest in understanding the effects that wind power can have on the power grid and operations.

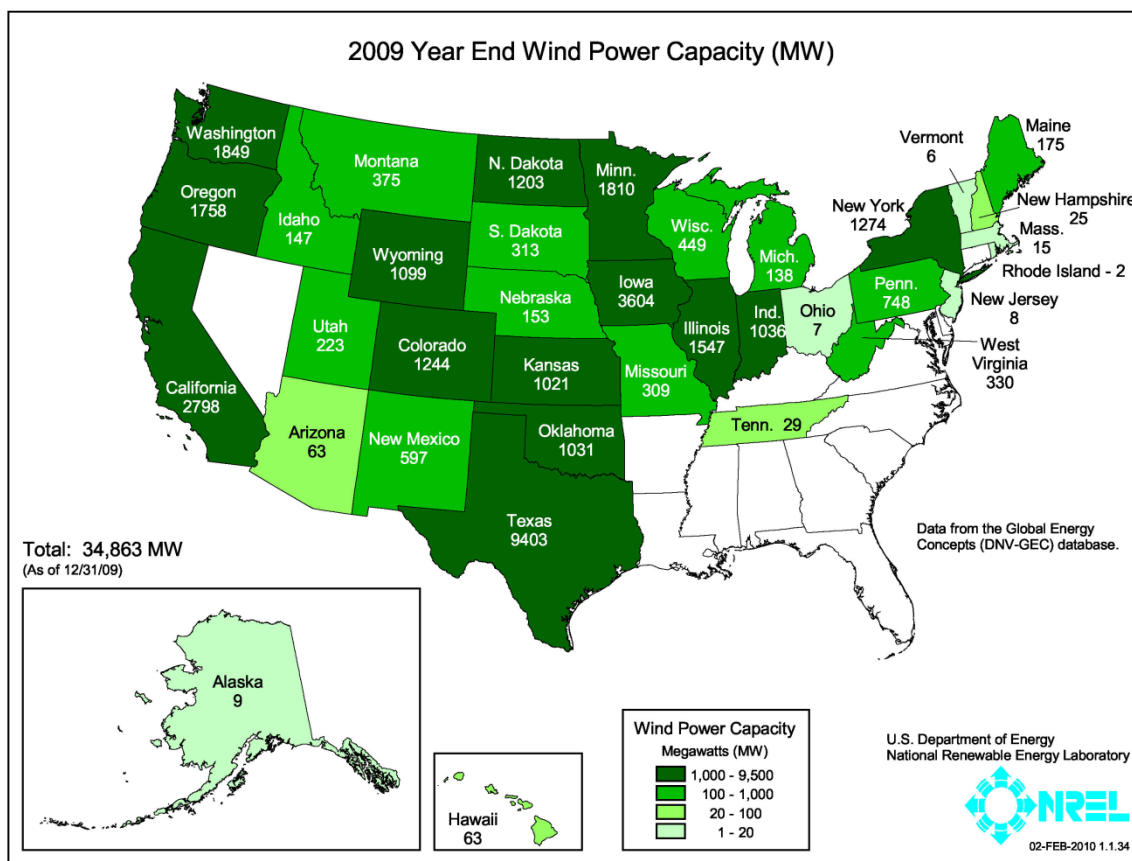
Figure 1: Renewable Portfolio Standards by State



Source: <http://www.dsireusa.org/summarymaps/index.cfm?ee=1&RE=1>

The installed wind capacity in the United States is shown in Figure 2. Texas has the largest amount of wind capacity installed with over 9 gigawatts (GW) of capacity. Most states have some amount of wind generation installed, only 14 states have no wind generation installed. Wind capacity is growing quickly with installed capacity increasing by nearly 10GW in 2009. The wind capacities throughout the United States represent a variety of factors. Wind generation installation is driven to areas with good wind resources, with sufficient transmission in place, and with incentives to install wind capacity or requirements for renewable generation. The production tax credits (PTC) that wind power currently enjoys helps wind become the choice to help states meet their RPS goals. The United States has strong wind resources in the center of the country from North Dakota to Texas.

**Figure 2: Wind Capacity in the United States**



Source: [http://www.windpoweringamerica.gov/images/windmaps/installed\\_capacity\\_current.jpg](http://www.windpoweringamerica.gov/images/windmaps/installed_capacity_current.jpg)

Wind integration in this paper refers not only to the physical connections but also the operational changes that may be required. It requires studying wind in context of the rest of the power system to ensure a seamless incorporation. Integration requires study of the planning and control processes in power systems. Wind integration is about making the most of the

wind resources. This requires careful consideration for the design and operation of wind generation. Integration also requires understanding of the power grid and its operation. Combining the two together integration studies attempt to maintain the reliability and efficient operation of the grid with wind resources. Current wind integration studies focus on the operations of power systems with high penetrations of wind. Early studies focused more on connecting wind to the power system. While integration studies do have some amount of transmission planning they do not have the detailed analysis necessary to construct new transmission. It is often impossible to truly separate wind integration from other changes to the power grid. As such studies are often performed with the primary focus on wind because it makes up the largest addition, but other technology such as solar is included.

## **1.1 Scope**

This report reviews the latest studies in wind integration and summarizes the results and recommendations for integrating wind power. The primary focus of this study is on integration reports within the United States released between 2007 and 2010. These studies benefit from more mature analysis techniques developed over years of integration studies as well as more experience with wind power as it has grown over the past several years. The most recent studies include a diverse group of studies representing a variety of areas throughout the United States. Wind integration studies have been performed for a wide variety of areas all around the world. The methodologies have been enhanced and refined. Early studies studied methodologies as much as wind integration. Other reviews have summarized and compared previous integration reports and international experience [16, 17, 18]. The general findings and recommendations for most integration studies are very similar. This report attempts to focus on a smaller number of studies and provide more details about similarities and differences of the studies and the results. The main studies reviewed in this report are summarized briefly below. Table 2 lists the main studies reviewed for this report.

**Table 2: List of Integration Studies**

<b>Study Name</b>	<b>Prepared by</b>	<b>Date</b>	<b>Shortened Name<sup>2</sup></b>
Operational Impacts of Integrating Wind Generation into Idaho Power's Existing Resource Portfolio [1,2]	Enernex	Feb-07	Idaho
Avista Corporation Wind Integration Study [3]	Enernex	Mar-07	Avista
Intermittency Analysis Project: Final Report [4,5,6]	GE	Jul-07	CEC IAP
Arizona Public Service Wind Integration Cost Impact Study [7]	Northern Arizona University	Sep-07	Arizona
Integration of Renewable Resources [8]	California ISO	Nov-07	CAISO
Analysis of Wind Generation Impact on ERCOT Ancillary Service Requirements [9]	GE	Mar-08	ERCOT
20% Wind Energy by 2030 [10]	NREL	Jul-08	20% by 2030
Montana Wind Power Variability Study [11]	Genivar	Sep-08	Montana
Eastern Wind Integration and Transmission Study [12]	Enernex	Jan-10	EWITS
Nebraska Statewide Wind Integration Study [13]	Enernex	Mar-10	Nebraska
Western Wind and Solar Integration Study [14]	GE	May-10	WWSIS

## 1.2 Power System Operations

Wind power can have a variety of impacts on the power system as its penetration is increased. To properly understand all the impacts, an understanding of power systems<sup>3</sup> operation is

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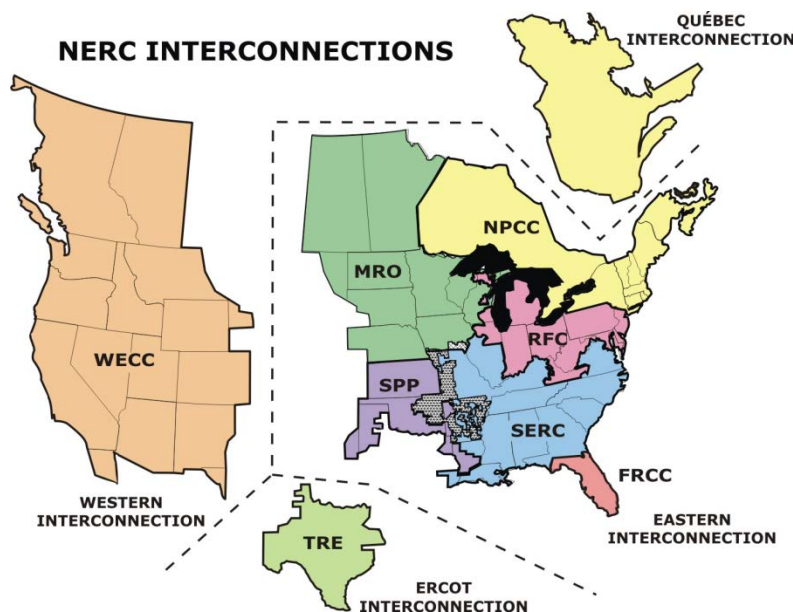
<sup>2</sup> The shortened name is an abbreviation for the study which is used throughout this paper to refer to the studies.

<sup>3</sup> In power systems operation, power and energy are often used interchangeably, even though they have different meanings. Power is the instantaneous rate of energy delivery. Energy is delivered over time at a certain rate of power. Power is measured in watts (W), megawatts (MW), or gigawatts (GW). Energy is usually expressed in terms of the average power over an hour, in megawatt hours (MWh), of gigawatt hours (GWh).

important. At its most basic level the power system is primarily made up of three main elements: generation, transmission, and load. The state of the power system is constantly changing due to changing loads, generation, transmission flows, interchanges, and unexpected outages. The generation and load must be balanced at all times. Electricity is consumed as it is generated and cannot be stored as electricity. Generation is the most controllable element and is relied upon to maintain the balance as the usage changes. If there is too much generation it can cause components to overload or burn out. Too little generation will lead to brown or black outs. Load or generation can change rapidly and unexpectedly, as a result sufficient flexibility must be maintained to quickly rebalance the system. Wind generation with its intermittent and variable nature adds another source of variability to balance with controllable resources. Reliable operation of the power system is critical and maintaining the reliability is the primary focus for the system operators.

The North American Electric Reliability Corporation (NERC) is responsible for setting the reliability standards of the power system. The electric system within the United States has three main interconnections and has ties to Canada and Mexico, **Figure 3**. The eastern interconnection covers from Florida into Canada along the east coast and west to Nebraska. The western interconnection covers from northern Mexico to British Columbia to Colorado and all along the pacific coast. The third interconnection is the Electric Reliability Council of Texas (ERCOT). ERCOT covers the majority of the state of Texas. Within the interconnections are reliability regions responsible for system reliability within their regions. There are six reliability regions within the eastern interconnection and one each within the western connection and the ERCOT connection.

**Figure 3: NERC Interconnections and Reliability Regions**



Source: [http://www.nerc.com/fileUploads/File/AboutNERC/maps/NERC\\_Interconnections\\_color.jpg](http://www.nerc.com/fileUploads/File/AboutNERC/maps/NERC_Interconnections_color.jpg)

Within the reliability regions are balancing areas. There are over 100 balancing areas within the United States. Balancing areas range in size from individual cities, such as Sacramento, to areas that cover several states, such as the PJM<sup>4</sup> interconnection. The balancing areas are responsible for controlling the generation within their area and coordinating with neighbors to control their interties. Balancing areas are also responsible for operating the system within the regulations set by NERC and the appropriate reliability regions. Balancing areas operate the system to minimize the Area Control Error (ACE). ACE<sup>5</sup> is a measure of the balancing area's deviation from intertie schedules in relation to the interconnections frequency on a continuous basis. A number of reliability standards are based on the ACE performance. System operators actively control the system to keep the ACE as close to zero as possible.

### 1.2.1 System Control

The reliable operation and planning in power systems require consideration of a wide range of timescales. Resource adequacy and capacity planning takes place on scales of one year to several years, this includes transmission and generation siting, sizing and construction. On shorter time scales in the range of days to months, maintenance planning is done. Generation and transmission facilities plan scheduled maintenance far in advance and coordinate with other facilities to minimize grid disturbance. In the range of hours to days, the unit commitment and scheduling processes are done, in these processes generation is selected to

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4 PJM Interconnection is a regional transmission organization (RTO) that coordinates the movement of wholesale electricity in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia.

The equation for ACE is:

$$ACE = (NI_A - NI_S) - 10B (F_A - F_S) - I_{ME}$$

where:

- $NI_A$  is the algebraic sum of actual flows on all tie lines.
- $NI_S$  is the algebraic sum of scheduled flows on all tie lines.
- $B$  is the Frequency Bias Setting (MW/0.1 Hz) for the Balancing Authority. The constant factor 10 converts the frequency setting to MW/Hz.
- $F_A$  is the actual frequency.
- $F_S$  is the scheduled frequency.  $F_S$  is normally 60 Hz but may be offset to effect manual time error corrections.
- $I_{ME}$  is the meter error correction factor typically estimated from the difference between the integrated hourly average of the net tie line flows ( $NI_A$ ) and the hourly net interchange demand measurement (megawatt-hour). This term should normally be very small or zero.

5

Source: NERC: [http://www.nerc.com/files/BAL-001-0\\_1a.pdf](http://www.nerc.com/files/BAL-001-0_1a.pdf)

provide for the forecast load. To adapt to any forecast errors or unplanned events generator dispatch is done on the minutes to hours time scales. Automatic Generator Control (AGC) which dispatches generation automatically to keep the system balanced operates on the seconds' timescale. A number of other automatic controls including generator governors, automatic voltage regulators, power system stabilizers, special protection and remedial action schemes operate on the milliseconds to seconds' timescales. Most planning is done on the longer time frames from years to days, while the operations timeframes range from seconds to days.

System operators use the same basic planning and balancing functions to maintain reliability but there can be many variations in each of the processes between balancing areas. These differences can lead to differences in the wind integration effects. Short term operation of the power system is done using a forecast of the demand; typically this begins a day ahead of the operation time. Generation is committed and scheduled to meet the load forecast in the most efficient manner considering hourly time steps. This process of forward scheduling involves a unit commitment algorithm to determine with sufficient lead time which generation is needed. The unit commitment is co-optimized with the generator schedules. The objective of the optimization is to serve the forecasted demand in the most efficient manner while respecting transmission, reliability and operating constraints. Network models to calculate projected power flows are used within the optimization process. Network models are usually full representations of the high voltage transmission and generation within the system, with load assigned to distinct points for the distribution network. Transmission will have loading limits and electrical properties within the model, and generation will have the operating constraints as well as costs. The network models serve as constraints to the optimization and ensure that power will flow in a reliable manner.

Committing generation to serve load is a very important process for reliability and to minimize system costs. Generators must be committed in advance of their scheduled operation because it can take many hours for them to start up. If too much generation is committed it is costly, inefficient and in extreme cases can overload system components. If not enough generators are committed in advance other power will have to be procured or blackouts will be risked. The resource pool to procure more generation will be diminished because there is insufficient time for many units to respond. The units capable of responding are likely to be expensive gas turbine units. Both under commitment and over commitment of generation can lead to higher energy costs.

Dispatch of generation is another important part of operating the power system. In dispatch the units that are committed are given schedules to follow. There are three basic categories of generation which determines the extent that they are dispatched: base load, intermediate load and peaking generation. Base loaded typically operates at its forward schedule and is rarely dispatched away from that point. Intermediate generators perform most of the changes in output. They will typically ramp to minimum at night, or shut off, and then ramp up with load the next day. The third type of generation is peaking generation, which is started and used for only extreme conditions. Forward scheduling is done along with the unit commitment process

and accounts for the majority of energy schedules. Dispatch of generation away from its forward schedule makes up a small part of the overall energy flows. Dispatch away from the forward schedules to reflect forecast error is usually called load following. Load following is an important consideration in many studies, because wind provides uncertainty and variability to the system that needs to be balanced.

Keeping the power system balanced and reliable requires more than adjusting the supply energy. Reliability-related services<sup>6</sup> are a group of services that are necessary to maintain operation of the power grid. There are a wide range of reliability related services that vary by region. Reserves, regulation, voltage support, black start capability, are all examples of reliability related services. Ancillary services are a subset of reliability-related services which include operating, contingency, and regulating reserves. Ancillary services are used to maintain short term balance of the system and recover from unexpected outages. Ancillary services provided by generation reduce the amount of energy a generator can supply when it supplies ancillary services. Operating reserves are made up of unloaded generating capacity which is synched to the power grid and capable of responding in a certain amount of time. Operating reserve is a very broad term which includes the ability to provide spinning reserve, regulation, supplemental reserve, and load following. Contingency<sup>7</sup> reserves are power system reserves which can be called to respond to a contingency event, or are interruptible loads which will reduce consumption.

Power systems maintain a few dedicated operating and contingency reserves to meet their reliability needs. They purchase these reserves from generators who reserve that capacity in case they are need. Spinning reserve is a common ancillary service used as an operating and contingency reserve. Systems procure an amount of spinning reserve which is synchronized to the power grid and available within 10 minutes. Non-spinning reserve is another reserve used for contingency reserves. Non-spinning reserve is offline capacity that needs to synchronize and deploy within 10 minutes. The levels of spinning and non-spinning reserves that systems maintain is related to the system size, the largest single contingency, and the makeup of the generation fleet.

Regulating reserves or regulation is also a form of operating reserves that systems maintain as a specific product. Regulation is the most flexible of the reserves it must be able to increase or decrease supply and is adjusted in seconds as opposed to minutes for the other reserves. Regulation is a reserve that is maintained to provide short term balancing of load and generation. Regulation is a flexible reserve; it is dispatched by AGC every few seconds to maintain ACE. Regulation is not an energy service; it is used to adjust the power balance. The

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<sup>6</sup> Reliability related services are defined in the NERC functional model:  
[http://www.nerc.com/files/Functional\\_Model\\_V5\\_Final\\_2009Dec1.pdf](http://www.nerc.com/files/Functional_Model_V5_Final_2009Dec1.pdf).

<sup>7</sup> Contingency is defined as an unexpected loss of a system component

dispatch process tries to adjust generation to send regulation back to zero, so that it is continuously available.

The amount of reserves a system maintains depends primarily on the system size. All systems maintain some degree of all the reserves but have a wide variety of mechanisms for procuring and implementing. The power grid must be managed in a way that a single contingency will not affect the security of the grid. NERC has specific requirements for the amount of spinning and non-spinning reserve that must be maintained by a balancing authority. The requirements have to do with system size, contingency size, and type of generator resources. The system must be able to recover from a contingency in a certain amount of time to be prepared for the next one. Spinning reserves and non-spinning reserves are deployed following contingencies, and are not used during normal system operation.

The control of the power system is something that is regulated and measured. The system performance is determined from observing how well balancing areas are able to perform some basic functions. These include meeting the demand including the required reserves, maintaining the system frequency, and keeping the intertie to their scheduled values. These are measured through the control performance standards (CPS). There are two CPS<sup>8</sup> which balancing areas are required to meet certain performance criteria, CPS1 and CPS2, both of which are measured using the ACE. The CPS standards ensure that balancing areas maintain a low ACE and have enough control to keep the system balanced. The CPS1 is primarily a statistical measure of the variability of a systems ACE. CPS2 sets bounds and standards to limit the magnitude of ACE. The CPS2 score is largely a measure of a balancing areas ability to keep its ACE from exceeding an allowable value. These standards are constantly being reviewed and replaced as better metrics become available. It is not uncommon for integration studies to directly indicate impacts in terms of ACE or CPS.

### 1.2.2 Operations Structure

System operators need to perform unit commitment, scheduling, and dispatch but there are a variety of ways to do each function. There are two principal structures to handle the unit commitment, scheduling and dispatch. The first is the vertically integrated utility structure. This is the classical structure in which a single entity owns all the generation and transmission and is responsible for serving a load. Utilities can operate independently or in power pools with neighbors. The second structure is the market structure. In a market generation and load are separate entities. Load must purchase generation to serve its load. Both these structures will serve the same purpose though the mechanisms will be different. In both cases there is an objective to minimize the system costs while meeting all of the load and reliability demands.

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<sup>8</sup> A more complete description of ACE and CPS measures is available from the NERC operating standards:

[http://www.nerc.com/docs/standards/sar/Draft\\_4\\_VO\\_Clean\\_Operating\\_Standards\\_01\\_07\\_05.pdf](http://www.nerc.com/docs/standards/sar/Draft_4_VO_Clean_Operating_Standards_01_07_05.pdf)

The unit commitment and forward scheduling process can be either through a market process or a vertically integrated utility with some slight variations. A market process will allow the generation to bid in prices and adjust generation to meet the demand until system costs are minimized. The utility unit commitment process would use generator costs instead of bids, and it would attempt to minimize total production costs. Both processes will be subjected to a model of the physical system to ensure that the forward schedule is feasible. The key piece of a market structure is the locational marginal price (LMP). LMPs are prices for the next MW of power at each node on the power grid. The LMPs represent the true price of serving load at each point of the power grid. LMPs will differ due to losses and transmission constraints on the power grid. The system will be optimized to keep the cost of energy as low as possible, while reflecting the constraints. Markets provide clear signals for investment and system upgrades. They line up the economics with the system operation.

As one moves closer to the actual operating hour, there is typically another process to adjust the previous schedules referred to as load following. Load following allows the system to make up for forecast errors in load; the hourly scheduling blocks, and adjusts to other unexpected changes. Load following is where market structures and utilities differ the most. Many utilities still use an hourly time step, while markets often switch to sub hourly steps ranging from five minutes to 15 minutes. After this adjustment most of the generation and typically any tie lines with neighboring areas are fixed for the interval. Any forecast errors or variability within the load following time step is met with regulation through the AGC system. Systems with long scheduling steps need to maintain more flexibility to handle changes than systems with shorter scheduling time steps.

### **1.3 Wind Generation Characteristics**

Wind generation converts the kinetic energy in the wind into electrical energy. Wind generators have several key differences with conventional generation<sup>9</sup> that supplies the majority of the nation's electric power. Understanding the differences is important to achieve maximum benefit from wind energy. Wind generation is a variable, intermittent, and uncertain resource. These characteristics are driven by the weather, and are typically not a concern with generation that uses conventional fuels. These characteristics are the reason there is so much concern with adding wind to the power grid. In addition to the differences driven by fuel there is other operating characteristics differences driven by the generation technology used in wind generation. Another important factor to consider with wind generation is the location of the resource.[15]

Intermittency describes the wind's nature to come and go, to be available to produce electricity sometimes, but be unavailable other times. Most areas have distinct weather patterns for when the wind blows. California tends to have a diurnal wind pattern with the period of strongest wind occurring at night, with the day experiencing lower winds. In addition to the diurnal

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<sup>9</sup> Conventional generation refers to power derived from gas, steam, or hydro turbines which drive permanent magnet generators. Fossil fuels are the primary energy source for electricity generation in the United States.

pattern there are also seasonal patterns for winds with the most productive periods occurring in spring and summer with the fall and winter being less productive. Other areas may have significantly different wind patterns. These wind patterns can be very important if wind power is playing a large role in supplying electricity. Intermittency is in contrast to most conventional generation which has a fuel that can be stored used on demand. The intermittency can affect the system's resource adequacy calculations. The system operators will need to determine if the wind is likely to be available during the system peaks or if other generation will need to be available.

In addition to this longer term intermittency wind power is also variable in nature. Variability describes the wind's tendency to change speeds as it is blowing. The variability of the wind can happen in seconds as gust blow through, or in longer time frames as regional weather patterns change. Because wind generation is weather dependent it is sensitive to the fluctuations of the weather. This variability is in contrast to most conventional generation can generally choose its desired generation level and maintain a steady output. Wind variability gives the operators another source of variability to consider other than the load.

Uncertainty of wind generation is caused by the intermittency and variability of wind generation though it can pose a different set of challenges. Uncertainty is related to the unknown future wind conditions. Even with certain repeatable weather patterns, prediction is not an exact science. The output of wind generation is unknown ahead of time, forecast can help bound the problem and often give quite good estimates, but compared with generation that can predictably operate at a certain output wind generation presents a challenge.

The electrical generator characteristics of wind generation also differ from conventional generation. Conventional generators use permanent magnet generators which operate at fixed speeds to produce power. Permanent magnet generators provide inertia for the grid; the electro-mechanical link helps resist changes in system frequency. Wind generation however has used induction generators (IG). The electrical differences of wind generation are primarily a concern for transmission design, which typically isn't covered in recent wind integration studies.

Location of wind generation is another difference from most conventional generation. With fossil fuel generation it is possible to transport fuel to a generator so the location is not as constrained by resources. Wind resources are often located far from load centers and far from main transmission pathways. While conventional generators can be located much more flexibly on the transmission system, wind generators are limited to where there is sufficient resource. Remote resources often require large transmission upgrades to connect wind to the system. The transmission upgrades for wind will have a set of design considerations specific to wind generation.

Wind generation in the power system is described as having a penetration level. There are several different ways to define the relative amount of wind generation in the power system. The energy penetration is the ratio of energy produced by wind generation to the ratio of total demand over the same time. Typically the energy penetration is expressed on an annual basis.

RPS standards are usually defined in terms of energy penetrations. Capacity penetration is the ratio of the installed capacity of wind generation to the historical peak demand of the system. Finally the instantaneous penetration is the ratio of the wind energy production to the system demand at that time. Instantaneous penetration can also be calculated over short periods of time, for example the hourly time step of a production cost simulation. While penetration is a good way to compare systems of different sizes there are often significant differences between systems which may drive the impacts to be significantly different at similar penetration levels.

High penetrations of intermittent generation impact all of the timescales of power systems operations. Current wind integration studies focus on the impacts on the timescales ranging from the AGC regulation impacts to the resource adequacy timescales, leaving the other impacts to be studied when specific projects are proposed. These timescales are often referred to as operational timescales because there are several important operations such as unit commitment, scheduling, load following, and regulation that all fall within this range. Wind generation can impact both the results of these processes as well as how these processes are performed. With higher penetrations of wind generation unit commitment algorithms take wind forecasts into account to avoid over commitment of generation which could risk over generation conditions. Generator schedules will be affected as more expensive generation is displaced for less expensive wind energy. The load following process will need to adjust for the load and wind together rather than just the load.

## CHAPTER 2:

# Integration Studies

Wind integration studies are performed for a variety of different reasons, and can have a wide variety of important differences. Wind integration studies do however have a fair amount in common even among the most different. They are after all studying the wind power and its interaction with the power grid. Often times wind is only one focus of an integration study. The studies are usually to address RPS goals which specify renewable levels, but not which type of renewable. Wind is generally the largest contributor but solar, geothermal, and hydro can all factor in.

### 2.1 Study Framework

Wind integration studies can vary widely in content and results, though they have a common framework. The common integration study framework is helpful in comparing studies. The common framework defines the study goals, describes the analysis, shows the results and derives conclusions.

#### 2.1.1 Study Objectives

Outlining the studies objectives is a very important part of an integration study. The goals will list the main objectives of the study, and often provide some background on why the study is being performed. The objectives will shape the analysis in a variety of ways. Studies commonly study integration costs, reserve requirement changes and in particular the regulation changes, load following requirements, ramping requirements, emissions changes, displaced generation, and transmission requirements. Wind integration studies are conducted to address specific concerns. The operation of the power grid is a complex endeavor and assumptions are targeted to facilitate the study results. Determining the integration costs are of primary concern in several studies though other studies disregard costs completely. Some methodologies can provide a wide range of information on impacts, while others target specific impacts in great detail. Since this is a diverse range of objectives and systems are very different, direct comparison even for studies attempting to quantify the parameters can be misleading. Objectives often correspond with the organization conducting the study. System operators often have narrow reliability focused objectives. Policy makers are often interested in impacts on costs and emissions.

#### 2.1.2 Scenarios

Describing the scenarios the study is using to accomplish the goals is another common part of integration studies. These sections introduce the system to be studied and the changes or additions that are being made to perform the study. The scenario descriptions will describe the current system and proposed changes. The scenarios can be partly defined by RPS, but actual build outs will need to be defined. It is very common for studies to include multiple scenarios. The scenarios can represent different levels of wind generation on system. Examining effects of diversity of wind generation is another common reason for performing. This is usually done by having creating scenarios with the same amount of total wind generation, but with it utilizing

different wind resource areas. Wind generation can be compared by installed capacity or production.

Another important part of the scenario is the description of the power system. There are a large variety of different systems within the United States. The size of the system is one of the critical factors. Larger systems often can have easier time incorporating wind. Larger systems take advantage of aggregation. The load variability scales more slowly than the load. Larger systems often tend to have a larger and more diverse generation fleet. The physical infrastructure of the power grid is also an important consideration. The makeup of the generator fleet can also impact the studies. System that are hydro dominate often have many fast moving generators available. Coal, natural gas, and hydro generators have different characteristics and the overall system capabilities will depend on the mixture of generators. The operations of the system are also important, is it a market system, what are the scheduling periods, and so forth. There are also systems that are net importers, or net exporters. The ERCOT system is essentially an islanded system.

One important factor is if systems are modeled in isolation or as part of the interconnection. The interconnection can be modeled explicitly using a network representation, or implicitly using constraints on the boundaries. Some model of the interconnection is needed to get realistic system performance with the exception of islanded systems. Implicit and explicit modeling both need realistic constraints. If the rest of the interconnection is modeled the assumptions for other areas are important. The neighboring areas are likely to make changes, if they add wind generation also the past interaction may not be realistic. In isolation it is important to make reasonable assumptions about the imports and exports and how dynamic they can be. Assuming no changes to imports and exports can place unreasonable burdens on internal generation to accommodate wind generation. Unrealistic constraints on imports and exports can hide the impacts outside of the system being studied or place unrealistic strain on the study system.

Part of the methodology is identifying the original data sources that are being utilized and explaining how the source data becomes the data for the study. The study scenarios are one important section, and creating the scenarios is part of the methodology.

### 2.1.3 Methodology

The methodology section is crucial to understanding integration studies. The methodology describes the how the study achieves its goals. Studies often have many stages of the analysis. The methodologies will include many statistical methods as well as many operational methods. Methodologies have changed as more integration studies were performed. Early wind integration studies were concerned as much about the methodology as the results. As more studies were performed some common practices evolved. Many studies now share some common analysis techniques, though there can still be many important differences. Even if studies share an underlying methodology there can still be significant differences in assumptions or parameters that will make direct comparison of results difficult. Comparing the details of the methodologies between studies is as important as the comparison of the results.

Assumptions are a key part of the methodology section. Assumptions are necessary because not everything can be known or modeled directly. The assumptions that studies make can have significant impacts on the results. It is important to consider all types of assumptions. All assumptions impact the methodology. Some assumptions are made to simplify aspects of operations that are either difficult to model or may not be relevant. Some assumptions are made to make up for lack of information or data. For assumptions that will have large impacts on results several sensitivities are usually performed to fully understand that variables role.

#### 2.1.4 Results

The results sections of integration studies present and discuss the results of the analyses. Results are often compared to present day or to the same year with a conventional generation build out. Comparing the results to a base case is necessary to understand the relative magnitude of the impacts. The results sections in the studies differ not only from what is originally studied.

Methodology is one of the primary factors in creating the results. The methodology determines what the results are and in which format. Studies that examine the same issue can present the results in different ways. Studies that look at cost impacts will often try to change all of the results into a cost basis, while other studies may have results on a MW basis. The assumptions and model parameters are another factor of the methodology which can impact the differences. Even with similar methodologies there can be differences which will drive the results. These differences can be efforts properly capture the operations of the system.

The results format is very important especially when attempting to make comparisons of results. Results can be expressed in absolute or relative values. Results can also be translated from their raw form into other forms. For example studies may have results in terms of MW, but they will convert them into a cost. Wind penetration is another driver of results. Many studies consider different levels of wind generation. Penetration is an easy way to compare results. The impacts of wind generation on the power system very often depend on the penetration.

Power system differences between different areas are another one of the key drivers of the results. The size of the system is one such factor. Larger systems have more diversity and are generally better able to adapt to changes. Resource mix is another factor, systems with flexible generation and transmission will generally have an easier time. Interconnection strength is another. Islanded systems must balance themselves while it is possible for systems within interconnections to coordinate with neighbors to help manage wind power. Operational differences between areas can also influence results. Systems with more frequent scheduling will have an easier time adjusting to changes than those with longer scheduling blocks.

#### 2.1.5 Conclusions and Recommendations

The conclusions section will typically address the goals of the report by analyzing the results of the conclusions. The conclusions are related to the goals of the study. Commonly studies conclude the system will remain operable with the additional wind generation. The details of the operability can vary greatly though. Some studies find that wind will greatly increase

operating cost and can provide some significant challenges. Other studies find that wind will require some modest changes but won't greatly impact the system. The goals of the study are directly addressed in the conclusions.

The recommendations are equally important as conclusions. Recommendations typically fall into two categories; recommendations about managing impacts and recommendations for further study. Many of the recommendations for managing the impacts will also require further study to properly implement them. The studies are very similar with the recommendations. The recommendations are targeted to mitigate impacts of the wind generation and since the impacts are similar the techniques are as well.

## CHAPTER 3:

# Study Scenarios and Methodologies

Integration studies are tailored to address specific issues that are set out at the start of the study. The methodologies that studies use are selected with the desired outputs in mind. Differences in methodologies are often driven by system size and complexity, availability of data, operating characteristics, resource mix, and scope. In addition to the physical characteristics of the power system being studied, the methodology of the analysis is one of the key drivers of the study results. One of the key first steps to perform a study of wind impacts is to create the scenarios to study. The wind scenarios are then usually fed into the simulation methodologies along with other information and the results are calculated. There are two primary categories for the analysis methods used in integration studies; statistical and operational<sup>10</sup>. Within each of these categories there are several ways to implement the methodology. All of the different methodologies produce a set of results. In many cases, even though similar results are obtained, direct comparison is difficult due to the differences in methodologies. The results from the studies consider a wide range of potential wind generation impacts. This next section highlights the similarities and differences between various approaches and compares the results.

### 3.1 Scenario Generation

Generating the scenarios is an integral part of performing a wind integration study. Wind integration studies examine future periods with more wind generation capacity installed so historical wind data isn't sufficient and additional data must be synthesized. Depending on the complexity of the study simply estimating the future wind resources probably won't be enough. An estimate of the future load is also necessary, using historical load and prescribed growth rates. Additionally other generation or transmission may be added to the system. There may also be other changes that could affect operations such as aggregating balancing areas, or emissions restrictions. The amount of detail needed for each scenario depends on the desired results, methodologies and the system.

#### 3.1.1 Wind Data

Synthesis of wind data in some form is common among wind integration studies. Because the wind generation profile is central to most wind study methodologies, the synthesis of the data can directly affect the results. The methodologies for wind data synthesis are very common. First a future build-out, or typically more than one, of wind generation is designed. Wind generation build outs can be designed to address many different concerns, for example best resources, close to existing load or transmission, and so forth. Some studies such as Arizona

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<sup>10</sup> There can be significant overlap between statistical and operational methodologies. This paper treats methodologies seeking to mimic aspects of system performance as operational. Methodologies based mostly off the characteristics of the wind profile are considered statistical. It is possible to derive operational results from statistical methods.

specify plant configurations directly, while others approximate them based on the installed capacity of a plant. Since wind power output is one of the primary requirements for both operational and statistical analysis its synthesis is very important to the final results.

WWSIS is a good example of different site selection concerns that it addresses using three different build out cases. One build-out utilizes the best wind resources regardless of location requiring significant transmission expansion. Another scenario prioritized resources close to load that could make use of existing transmission, even though the best resources may not be used. The third scenario was a hybrid of the previous two, maintaining a balance between using the best resources, and minimizing the amount of new transmission needed.

After the build outs are selected a historical time period is chosen and observed weather data is fed into a model to produce wind speed at the desired sites. The data used could come from some existing wind sites and direct measurements at future sites, as in the case of Montana and Avista. Many studies also make use of numerical weather prediction (NWP) models to create wind data. In these cases the models are set up with a mesoscale grid, and using historical data they are run and the weather at future wind plant sites is recorded. Additional wind measurements from existing sites or from developers are often used to augment the models. Arizona, ERCOT, Nebraska, EWITS, Idaho, all make use of these general techniques. Some wind integration studies separate the development of wind scenarios from the integration studies. The EWITS and WWSIS studies both have separate detailed studies identifying the scenario generation methodologies [20, 21].

Once the wind speed data is synthesized, the wind based power generation must be derived. In addition to the wind speed data, wind power will depend on the turbine size used, the layout of the wind plant and the wind plant capacity. Most studies assume a particular type of wind turbine and use the appropriate power curve. Power curves for wind turbines are cubic in nature. The amount of power that can be generated increases more quickly than wind speed until the rated capacity. Long wind speed times-steps combined with the wind power curve can greatly impact the amount of wind energy calculated from a profile. It may mask the true generation profile if the average of a period is below the threshold, but the raw wind speed would have exceeded the threshold for part of the period. The time steps for the wind data is an important consideration both for the study and the wind data. Wind speed is often measured on a ten minute basis and NWP models used time steps that range from ten minutes to one hour.

Many studies are concerned with the impacts of wind on shorter timescales, such as a one minute basis. One minute wind data must also be simulated in addition to the data with the longer time-steps. The one minute data is synthesized using the wind data generated and adding variability that would be expected on the one minute basis. This process has a few parameters that can impact the results. One minute wind data is done solely as wind generator power data and not on the underlying wind speed data. The one minute variability itself is also of concern. Most studies rely on taking one minute variability from a different existing wind plant, and applying it to the profile. The variability therefore needs to be extracted from the longer term changes. Attention also needs to be taken if the variability is dependent on other

factors such as production level of the plant. If actual variability is used and attached to the wind power data, it may not come from the same area, so the variability might not be entirely representative of that area. There could also be differences in the turbines and plant configuration which can influence the variability. Some studies, such as the Montana study, randomly generate variability based on observed data and apply it to the synthesized wind production.

Montana and Arizona are two contrasting examples of the wind scenario generation. The Montana study uses actual wind power data plus meteorological data from developers evaluating potential sites. The study thoroughly discusses the factors it considers important for the power conversion. It gives the details of wind plant powers curve based on the single turbine power curve and the expected turbulence and variation of wind speed within a wind plant. The Montana study also looks at how the performance of their simulated wind power compares with historical data. The study also does several sensitivities evaluating the effect the wind power curve, the wind plant size, the turbulence intensity, the air density, and wake loss on the wind energy profiles. These sensitivities show some of the complexity in modeling wind power. The Arizona study also gives significant details in its wind scenario generation efforts. In contrast to the Montana study the wind speed data is primarily developed using a NWP model run for a historic period to fill data in at locations where it wasn't directly measured. There are two main wind regions in Arizona that were modeled. The study also describes corrections to the data that were made for terrain which affects local wind speed but is too small to model in the NWP data. Corrections are made by comparing the NWP model output and observed wind speeds and correcting any inherent bias in the model. The Arizona study describes the details of wind plant configurations including using a specific turbine in the model and the layout of each wind site. The study also details how the wind speed data taken from the NWP model is assigned to the individual turbine locations which don't line up with the grid.

All of these factors have influence in the scenarios that are generated. The wind power scenarios are often the key input into the wind integration study. As more wind generation capacity is installed and more data becomes available, the ability to synthesize realistic data will likely improve.

### 3.1.2 Load Data

The load scenarios are often the simplest to construct though they are very important. Historical load is measured and archived in all control areas. It is used frequently for many types of studies as well as for load forecasting. The forecasts range from next hour forecast for operations, to multi-year growth forecasts used for transmission or generation upgrade studies. The load scenarios for wind studies are developed in a similar manner to transmission studies. Due to the strong influence of weather on load the load data is from the same time period as the wind data. The load is scaled up by a growth factor representing average yearly growth for each year between the historical year and the target year. More complicated methods consider the minimum, maximum, and average separately so that different growth factors can be used on each one. The load growth rates are specific to each area and are driven by a variety factors.

### 3.1.3 Transmission

Developing transmission scenarios can vary widely between studies in goals, detail, and sophistication. If the methodology in question doesn't model the transmission system, then it typically won't consider transmission upgrades at all implicitly assuming that necessary upgrades will be built. If detailed transmission plans are not required, studies may simply relax transmission constraints on the existing network. This effectively upgrades the system but still requires power to flow along existing paths. The more detailed the model the more detailed the transmission upgrades need to be. The starting point is the transmission plans that transmission operators continuously develop looking out 5-10 years. These plans are made to accommodate load growth and new generation on a regional basis. For wind studies additional transmission needs are determined by considering the deliverability of power from the wind resource areas to the load centers. Transmission needs are determined by the addition of the wind generation. Changes between scenarios are largely driven by changing the wind generation build outs.

## 3.2 Statistical Methods

Statistical methods are often the first analysis shown in a wind integration study. Statistical methods are flexible and provide a good first approximation of the impacts of wind on overall system performance. The methods rely primarily on the study wind generation profiles from the scenario generation phase as the inputs. Many studies also subtract the wind generation from the load profile to create a net load profile to base the analysis on. Statistical methods do not take into account operating constraints, nor do they try to realistically model the complex interactions of the power grid. Statistical models are used to estimate the additional variability added to the system, to evaluate the ramp rate duration and magnitude changes, frequency of large events, and the probability of concurrence of different events. Statistical studies use time steps as short as a minute, which can be cumbersome with other methods. Statistical models are used effectively to estimate impacts on services that are procured or dispatched on a system wide basis, such as regulation. Statistical methods are preferred for examining correlations, estimating benefits of geographic diversity, and isolating the effects of individual variables.

The variability of wind generation is most commonly studied using statistical methods. Variability is defined in different ways in different studies. Variability is often measured using standard deviation. Studies define it differently using the wind or the net load. Also some studies consider the change from time step to time step, while others will consider the change from an average interval of several time steps. A common approach is to study the variability across many time scales. It is common for studies to consider time steps which will span the range of their dispatch processes. In this respect the variability measures can estimate potential impacts on specific systems, without modeling those systems directly. The variability grows with capacity of wind installed, but on the short time scales less than 15 minutes, it grows more slowly than the capacity. The variability as a percentage of wind generation capacity often shrinks as capacity is added.

Statistical methods are also used to evaluate changes in wind resources with changing diversity. The effects that wind generation has can be different if it is spread throughout the system or

concentrated in a few areas. Wind generation in diverse regions tends to reduce the relative variability as compared with wind facilities concentrated in the same area. Some studies create different build out scenarios with the same capacity or same production so that the effect diversity can be observed. Montana, Arizona, and ERCOT all include scenarios with different amounts of diversity in the wind resource. Studies which consider diversity find the variability in the wind resource was lower for more diversified scenarios. Also the extremes in the wind generation are reduced with more diversity in the wind resources.

### **3.3 Operational Modeling**

Operational models are the main focus in most wind integration studies. In these methodologies a simplified model of the power system is studied with the expected future wind scenario. The system is then analyzed for changes that occur between a baseline, often times the present system, and the high wind penetration scenarios. Operational modeling comes in a few different forms. Production cost simulation is the most common type, used by Arizona, Nebraska, EWITS, WWSIS, IAP, and ERCOT. Production cost methodologies were developed for grid planners. They enable planners to study changes to the system in great detail before a new generator or transmission line is constructed. They are used to evaluate transmission designs and generation additions before they are constructed. Production cost models are generally quite robust and provide many possible outputs such as prices, costs, emissions, transmission congestion, and so forth.

While production cost is the most common operational model it is not the only one. Hydro optimization models are another operational model used in wind generation studies. Hydro optimization models are very similar production cost models. These models take into account detailed descriptions of the hydro generation facilities, including the complex constraints, and attempt to optimize the use of hydro to most benefit the system by lowering overall cost. Systems with large amounts of hydro generation like Avista and Idaho will use hydro optimization models instead of production cost models. A few studies use different operational models that take more simplified approaches. The more simplified models were developed and used in studies that had very targeted results. These models typically target one or two specific operations, such as dispatch. The CAISO study and the Montana study take this approach.

#### **3.3.1 Production Cost Model**

The methodologies behind production cost models are essentially the same with minor differences depending on the models. Production cost models mimic the unit commitment and dispatch operating processes. They use a representation of the power system; this can range from a very detail AC representation with every generator, line, transformer, and so forth, modeled to a very simplified DC representation in which many elements are aggregated together. The selection of the appropriate network model depends on the desired results, more detailed models are important for transmission planning, while general system level operating impacts can be produced from less detailed models. An hourly load profile is another input to a production cost model, for wind studies the wind profiles are also an input. The model then attempts to dispatch generation for a year, 8760 hours, to meet the load less the wind generation respecting any operating limits within the model. The generation is dispatched in the lowest

cost fashion, usually based on heat rates and fuel prices. Because production cost models have a high level of detail they can be used to produce many outputs. Due to modeling complexity and simulation time considerations, models are often tuned to only consider specific outputs, the models can still provide all the outputs but the results may not be as reliable. Production cost models are able to produce costs, prices, generator schedules, ramp rates, emissions, and transmission usage.

LMPs are an important output of many production cost models. While LMPs can be used to determine the system costs they provide a more detailed set of information. LMPs provide the price of energy at each location on the grid for each time step of the simulation. This information can be used to calculate revenues for generation, costs to load, and congestion costs. It can also be used to determine the viability of storage looking at peak and off peak price differences.

Production cost models are capable of studying a number of different factors. The generator unit commitment and dispatch patterns and total energy can be evaluated. This is very useful to see which generation is displaced and when with higher wind penetrations. Emissions can also be calculated using production cost simulations; some allow emissions limits to be a constraint within the model. Though the production cost models can report all these possible outputs, they typically are tuned to only a few of the outputs.

When running the simulation models some studies use multiple runs and compare them. This is helpful for isolating variables and understanding their effects on the greater system. A common variable to isolate is the wind forecast. One run uses a wind forecast with errors, and the next run uses the wind profile which adjusts the forecast run. This allows for more realistic unit commitment and dispatch from the models. And it allows the effects of the forecast errors to be included in the production cost models.

The ERCOT study is an example of a study using a production cost model for a more targeted scope. The ERCOT production cost model neglects many transmission constraints to allow delivery of the excess wind without the need to come up with detailed transmission expansion. ERCOT's primary interest was to determine the energy mix, and which resources would be displaced to accommodate wind.

### 3.3.2 Other Operational Models

Hydro optimization models are very similar to production cost models. The hydro optimization models are specialized production cost models for power systems with lots of hydroelectric generation. The models focus on the characteristics and constraints of the hydro system, often this means that the rest of the power system is modeled in less detail than production cost models. The objective of hydro models is to make the best use of the hydro system. Hydro models will often use prices as an input rather than something that is determined by the model, and will use the hydro generation to avoid high prices for energy.

The Idaho study uses a hydro optimization model. The model is similar to a production cost model, but it focuses on the use of a hydro facility. It has a simplified network model but very detailed models of the hydro generation. One of the major differences between hydro

optimization models and production cost models is how prices are determined. Because hydro models typically focus on optimizing hydro resources and do not try to co-optimize all resources, hydro models often use price of other generation as an input. Since price is an input, hydro models will try to run hydro when prices are high so that costs are reduced.

Production cost and hydro optimization models are the majority of operational models in use but there are other interesting operational models used by the CAISO and Montana. Typically these studies measure bulk system requirements, but do not have the detail to determine if the system is capable of meeting those requirements. Both models are much simpler than the production cost simulation models. These studies attempt to look at the system performance on aggregate by measuring the effect wind generation has on the system's ACE. The CAISO study approximates the expected ACE that would be achieved given load and wind profiles and forecast errors for both. The study assumes that the remaining generation would be dispatched in a way to provide the needed energy. The study measures the amount of short term control action that could be needed to cancel out the ACE caused by the variability and uncertainty. The Montana study has a similar approach which takes the measurement a step further. The Montana study looks the Control Performance Standard 2 (CPS2). CPS2 is standard which defines an allowable band for the system ACE, for each 10-minute period the average ACE must be within the defined band. If the ACE is outside of the band the period is a CPS2 violation. The Montana study measures CPS2 performance with their current control levels and future wind, and then looks at how much additional regulation is required to maintain the current CPS2 performance. These operational studies provide more detail of the impacts that wind generation can have on the system within the hour.

Operational models can also be used in series, with results from one step feeding into another. Production cost models are good with hourly analysis. Using the outputs of the hourly analysis with another methodology to look into the hour can provide useful results. Several studies employ another operational model in addition to its use of production cost modeling. A Quasi Steady State (QSS) model evaluates the system dynamics within the one hour blocks of the production cost simulation. The QSS simulations are run on specific 24-hour periods of interest. The statistical analysis provided the study scenarios, while the production cost model provided the inputs. The QSS simulation uses an extremely simplified zonal model dispatching aggregate generation within each area, based off the schedules from the hourly production cost results. Generation is aggregated by type, and assigned a priority and capacity for regulation and load following services. Priorities are assigned based on the dispatches from the production cost models. Imbalances from the hourly schedules and one minute load and one minute wind data are made up by dispatching to correct the imbalance from the units that can provide a particular service. Generic ramp rates and capacities are assigned to the generation. Imbalances that could not be corrected by the available units would contribute to areas of ACE. The areas were assigned bounds from which approximate CPS2 performance is measured.

### 3.3.3 Forecast Modeling

Many analysis techniques try to include wind forecast effects in the analysis. Statistical and operational models can easily measure the variability and intermittency effects but to

understand the uncertainty, forecast modeling is necessary. In addition to developing wind scenarios, wind forecasts are also modeled for many studies. Forecasting is seen as the best way to manage the uncertainty inherent with wind generation. Many studies try to use forecasts of some type in their models; this allows the mitigation effects of forecasts to be assessed. The forecasts used in the studies are generated in a few different ways. The forecasts are often used in an operational model, and compared to a perfect forecast, which is the same as the wind scenario generated during that phase.

Some studies generate persistence forecasts to go along with their wind generation data. This method is most similar to one that may actually be used in operation. The persistence forecast assumes the current generation continues. Persistence models can often be enhanced with some additional statistical models either based on the short term ramping, or other historic performance. One drawback of persistence forecast is that it is limited in the number of forecasts available. Different amounts of persistence can be used, and some statistical models can be added.

Other studies use forecasts which match historical forecast performance from their current operations. Forecasts are generated at the same time as the wind profiles using a similar NWP model, or using a random number generator. In both of these cases it is possible to create many different forecasts. This enables various statistics of forecasts to be isolated. These forecasts can be directly with many operational models, and compared to the actual wind profile. There are drawbacks to either technique of forecast modeling. The NWP models to generate the forecast will share underlying methodologies and data with the models that produce the wind profiles. The models may have similar errors within them which will affect the forecast quality. Using a random number generator to match the statistics of the forecast error may not be able to capture all of the relevant statistics to forecasts.

Many models will make use of wind forecasts directly in the model. The wind forecasts can be used in production cost models or other simulations directly in place of the wind generation profile. Running simulations with multiple forecasts and with the wind generation profile can expose the system to determine how much of the uncertainty forecasts can moderate. Additionally many studies will perform statistical analysis on the wind forecasts to understand how the uncertainty compares with variability.

Some operational models do not allow for forecasts to be used directly. In these models the forecasts are replaced by a firmness factor in the model. Instead of dispatching to a forecast value, the actual value is used, but the power delivery is not guaranteed, the models will acquire additional resources to compensate for the uncertainty. By adjusting the firmness factor uncertainty in the wind forecasts can be represented at different levels. The Arizona study uses a firmness factor, which is tuned by examining forecast performance. The firmness factor only represents the downside of uncertainty, it is impossible to tell if there could be over generation situations due to under forecasting.

## CHAPTER 4: Study Summaries

This section briefly summarizes the main studies highlighted by this report. These studies cover a large amount of the United States. There is a lot of variation between the studies in terms of system size, generation make up, and operating processes. **Table 3** shows a comparison of some parameters of the studies. The system size and wind penetration make up two of the biggest factors in determining the wind integration impacts.

**Table 3: Study Comparison**

Shortened Name	Peak system load (MW)	Max. Penetration on Energy (%)	Max. Wind Capacity (MW)
Idaho	3,085	30	1,200
Avista	2,100	30	600
CEC IAP	50,286	33	12,700
Arizona	7,905	10	1,260
CAISO	50,286	20	6,700
ERCOT	65,000	23	15,000
20% by 2030		20	
Montana	1,766		1,450
EWITS	529,857	33	225,000
Nebraska	7,550	40	4,727
WWSIS	58,087	30	75,000

### 4.1 Operational Impacts of Integrating Wind Generation Into Idaho Power's Existing Resource Portfolio – Feb. 2007 and Addendum Oct. 2007 [1, 2]

The Idaho study covers most of the state of Idaho excluding the Northwestern Idaho that is covered by Avista. The Idaho system has a peak load of 3085 MW. It primarily studies the system costs and operating changes required at the Hells Canyon complex, a 391 MW hydro station on the Snake River. The study looks at four penetration levels of wind generation, 300,

600, 900, 1200 MW. The study uses three study years to account for varying hydro conditions, using base years 1998, 2000, and 2005 to evaluate high, median, and low hydro conditions.

The main operational study uses a hydro based operating model which is similar to a production cost model. The model's primary function is to optimize the use of the hydro facilities subject to detailed hydro constraints, and less detailed electrical modeling of the remaining system. The model does not take into account how prices may change with wind, and relies on input prices for energy. A statistical model is used on ten minute load and wind data to determine reserve parameters for the hydro model.

The study reports the highest integration costs of the studies considered in this report. The study needed revision due to anomalous prices from the California energy crises that were used initially. The model results are very sensitive to the energy prices used. The results show that wind integration costs are \$7.92/MWh down from \$10.72/MWh in the original study. The study finds that the reserve requirements will increase with wind penetration. Interestingly the regulation increases as a percent of the installed capacity will increase with more capacity. The incremental regulation increase ranges from 24 MW to 157 MW.

## **4.2 Avista Corporation Wind Integration Study March 2007 [3]**

Avista is the utility for Spokane Washington and Eastern Idaho. It is a winter peaking utility with 2100MW peak demand, and 890MW minimum. The study considers the addition of 100MW, 200MW, 400MW, and 600MW of wind capacity on the system. The wind energy penetration levels range from 5 percent to 30 percent on energy. The Avista system is served largely by hydro power.

The study uses a hydro optimization model of the Avista system as the primary methodology for assessing the wind impacts. It performs a similar function to a standard production cost simulation model using a linear programming optimization dispatch model of the system. The model optimizes over a one month window with a 1-hour resolution; balancing generation, load, imports, and exports. A second model evaluates the impacts of intra-hour variability using the results of the hydro optimization model. The intra-hour model uses a 10-minute time step to evaluate the necessary control actions to keep the desired CPS2 performance.

The study evaluates the system costs and performs a number of sensitivities to determine the impacts of short term markets, rising forecast error, geographic diversity, and curtailment. It also looks at how integration costs change based on diversity, penetration levels, hydro availability, market price levels, and wind forecast errors. The study finds that wind integration costs increase as the wind generation increases, from \$2.75/MWh to \$8.84/MWh. Sensitivities with respect to wind forecasting show that approximately 35 percent of costs are attributable to day-ahead forecast uncertainty. The results also show that the integration costs will depend on the market prices, though the relation is not linear. The study included sensitivities on wind curtailment and found that wind integration costs could be reduced between 21 percent and 37 percent with no more than 1.4 percent energy curtailment. The study uniquely includes an analysis quantifying the benefits of adding 10 minute energy market in the northwest. The wind

integration costs drop between 39 percent and 62 percent from the base case with the more frequent scheduling.

### **4.3 Intermittency Analysis Project – July 2007 [4,5,6]**

The California Energy Commission undertook the Intermittency Analysis Project (CEC IAP) to evaluate renewable potential within California, understand the impacts of incorporating the resources, and to learn from other regions that have already large concentration of renewable power generation. The project was undertaken in part to understand the implications of California RPS policies. The analysis is very thorough evaluating wind turbine technology, examining transmission options to integrate generation to meet the RPS policies, the impacts on transmission, reliability, operations, and costs. The study has several components though the impact of intermittent generation on operation of the California power grid is most relevant to this paper.

The CEC IAP examines four scenarios for renewable generation growth within California, a 2006 base, 2010 with 3000MW new wind, and 20 percent renewable, and 33 percent renewable cases in the year 2010 and 2020 respectively. The CEC IAP includes additions of four types of renewable generation; wind, solar, geothermal, and biomass. Wind and solar are the primary concerns for the study. AWEA created wind data sets to study based off historical measurements of wind speeds for three years. The 20 percent renewable penetration case considers the addition of 7.5 GW wind generation and 1.9 GW of solar generation. The 33 percent cases consider up to 12.7 GW wind capacity and 6 GW of solar capacity.

There is a large amount of statistical analysis done of the wind, solar and load data. This analysis considers the variability and reserve requirements for the system. A production cost model was run for 3 years to represent a variety of different conditions. The model includes the entire WECC area, though the primary focus is on the impacts within California. Additionally some selected periods are examined with another operational model capable of using time steps smaller than one hour.

The study finds that wind generation displaces fossil fuel generation and imports to California. The hydro system in California will need to be increased roughly 50 percent from current practice to accommodate load growth and wind. The study estimates the additional regulation needed to be 20MW on 350MW with 20 percent renewable generation. The cost of the additional regulation is estimated at \$0.22/MWh intermittent generation. The study also concludes that increases in load following capability will be needed, an increase of about 10MW/minute to 130MW/minute. The load following increase needs to be maintained for 5 minutes.

One area the CEC IAP study that stands out against other recent studies is its analysis of intermittency impacts wind and solar resources on transmission reliability. This section of the CEC IAP looks in great detail at the California transmission system and the reliability impacts that significant amounts of intermittent generation could have on transmission. The report also examines designing transmission specifically for renewable generation. The study quantified congestion patterns that were likely to be seen under different weather conditions. The costs of

developing the transmission for renewable are estimated. The study also attempts to determine the correct approaches for designing transmission for intermittent resources, which may operate at capacity a small fraction of the time. The study identifies 74 new or upgraded transmission elements to accommodate the 20 percent renewable case, and 128 for the 33 percent case.

#### **4.4 Arizona Public Service Wind Integration Cost Impact Study – September 2007 [7]**

The Arizona study estimates wind integration costs in the state of Arizona. The Arizona system has a peak load of 7,095 MW. The study considers four wind penetration levels, 1 percent, 4 percent, 7 percent, and 10 percent of the annual energy demand. The installed capacity of wind generation ranges from 108 MW to 1260MW. The state has two primary wind regions which provide all of the energy. Several sensitivities of build outs between the two zones are analyzed to capture geographic diversity effects.

The Arizona study includes a very detailed description of how the wind generation scenarios are generated. It gives many parameters of its mesoscale model, and discusses some of the considerations, such as topographical features which could influence the results. The details of the wind plant siting and layout are also given. The Arizona study uses a production cost model tuned to estimate the integration costs from wind resulting from day-ahead uncertainty, hour-ahead uncertainty, and within hour regulation separately. The model simulates an entire year, using day-ahead and hour-ahead runs.

The study separates out the causes of the integration costs from day-ahead uncertainty, hour-ahead uncertainty, and intra-hour variability. The integration costs range from \$0.91/MWh to \$4.08/MWh. The hour-ahead uncertainty represents the largest cost component according to the study. Interestingly the within hour regulation costs are comparable at all penetration levels, and are actually slightly lower at the upper penetrations. The day-ahead uncertainty increases substantially from the 1 percent penetration level, though is steady at 4 percent, 7 percent, and 10 percent. The study also shows substantial differences in cost with changing diversity, the most diverse having the lowest incremental cost.

#### **4.5 Integration of Renewable Resources – Nov 2007 [8]**

California Independent System Operator (CAISO) performed a study focusing on operational impacts of increased wind generation. The system covers 75 percent of the state of California and has a peak load of 50GW. The study looked at the impacts of adding an addition 3700MW of wind capacity. The study uses data from the CEC IAP [4] study to ensure consistency between the two studies. The CAISO study is targeted to address specific operating issues such as transient stability, regulation, ramping, and over generation.

The study includes a section on transmission planning unlike many other studies. This section is a review of previous transmission plans for wind resources. The study reexamines a number of reliability issues related to the expansion to the Tehachapi wind resource area. The study uses updated wind turbine generator models to reflect newer technologies that were not used in

the original plan. The study finds that some of the transmission elements were not necessary with newer wind turbine generators.

The CAISO study performs statistical analysis on the wind generation, load and wind ramps and forecasts. The statistical models look at changes expected in the variability that the system will have to accommodate in the future. The study also includes an operational model designed to measure the amount of regulation and load following that would be needed. The model is a simplified model of the load following and regulation processes. The study models uncertainty impacts as well as variability impacts.

The study shows a significant increase in required regulation at different times of the day. Regulation needs are expected to increase between 100MW and 500MW, compared to the 350MW currently procured. Morning and evening ramps may also be increased by up to 1500MW over a three hour period due to the strong diurnal nature of wind generation in California. The duration and rate of load following and ramp events are also increased. Wind curtailment up to 500MW is suggested to mitigate over generation conditions. It is expected to be needed less than 100 hours per year. No integration costs are calculated.

#### **4.6 Analysis of Wind Generation Impact on ERCOT Ancillary Service Requirements – March 2008 [9]**

The Electric Reliability Council of Texas (ERCOT) system covers the majority of the state of Texas. It is not interconnected with the eastern or western connection with the exception of a few small DC ties. This makes the Texas system somewhat unique as it does not have neighbors to coordinate and diversify with. The system has a peak load of approximately 65GW. The integration study uses 5 scenarios ranging from 0 to 15000MW of wind capacity. The wind penetrations are up to 23 percent capacity to peak load penetration, and a 17 percent penetration on energy.

The study focuses on the impact of increased penetration of wind on ancillary services and in particular regulation. The paper has a large amount of statistical analysis which focuses on the combination of wind generation and load, or the net load. The study finds that even at the upper wind penetrations the majority of variability is driven by load events. The study includes a sensitivity to consider how geographic diversity of wind resources impact operations. The study analyzes the effects that wind forecasts can have on system performance. The study also does some analysis of extreme weather events and their frequency, magnitude, and impacts.

Production cost simulations are used in the study to determine operating impacts and costs. The existing ERCOT methodologies to calculate regulation requirements are used with the different scenarios to determine the effects of the wind on the magnitude. The study predicts modest increases in regulation reserves of roughly 50MW increase for the 15000MW wind case on top of 230MW for the zero wind case. Interestingly the results show the regulation requirements increase with wind, though the spot prices for regulation are reduced. This is due to more excess capacity made available by the wind offsetting conventional generation. The forecast

errors also contribute by causing less efficient commitment which leaves the excess capacity committed and running near minimum. Overall the ERCOT study predicts some of the lowest integration costs of any study. The low costs likely reflect how limited they are in scope. Integration costs incurred from regulation increases ranged from \$0.28/MWh to -\$0.18/MWh wind generation. The highest wind penetration had the lowest incremental regulation costs, and in fact the wind benefits the system costs.

#### **4.7 20 Percent Wind Energy by 2030 – July 2008 [10]**

Performed by the U.S. Department of Energy, this study takes a broad look at the issues that the country would face if it were to try to supply 20 percent of electric energy demand from wind power by the year 2030. It is very broad and includes sections examining turbine technology, manufacturing processes, materials, resources, and equipment and O&M costs. It is not a typical wind integration study that looks at the operating changes for specific wind scenarios. It gives very good information about all aspects of wind generation and how it may be able to contribute in the future.

The study takes a balanced view of wind plant siting and potential environmental effects. The study looks at the impacts wind generation could have on greenhouse gas emissions, water conservation, energy security and stability, and costs. It also considers potential negative environmental costs such as bird kill, and noise.

The study looks at the transmission requirements for integrating wind power throughout the U.S. It takes a national view of the best resource locations and the load centers and considers how wind can best be moved around. The study looks at a possible design of 12,650 miles of new transmission at a cost of \$60 billion. This study includes analysis of distributed wind as well as off shore wind energy.

This study includes a review of wind integration studies from 2006 and earlier, and uses them as a basis for analysis. The study concludes that the US possesses sufficient resources to power 20 percent of the electricity needs using wind energy by 2030. Doing so would require 300GW of installed wind capacity, compared to the 11GW installed by 2006. This would decrease greenhouse gases by 825 metric tons annually, and reduce the electricity sectors water use by 8 percent (4 trillion gallons). The prediction of the cost differential is a modest 2 percent increase over a conventional generation build out. In real dollars it is still a significant sum of \$43 billion. Spread out over the total generation it represents an increase of \$0.0006 per kWh.

#### **4.8 Montana Wind Power Variability Study September 17, 2008 [11]**

The Montana study covers the Northwest Energy controlled power grid in the state of Montana. The Montana system has a historic peak load of 1766MW. The study considers three wind growth scenarios 358.5 MW, 741MW and 1450MW of additional wind capacity. The diversity is also examined by comparing four build outs of the same capacity, though distributed differently for the 1450MW case. The study used the years 2006 and 2007 as the base years for the analysis.

The study includes detailed statistical analysis which isolates the effects of diversity, wind plant size, wake and array losses, turbulence intensity and density on wind production and variability. The study finds increases in variability are expected with more wind generation and higher concentration of resources. The study also uses an operational model to evaluate the potential impacts of wind on the CPS2 performance of the system and the system control. It is not a typical production cost model, but rather a custom model which looks at the effects of short term uncertainty and variability on the dispatch. The model simulates the total system dispatch needs neglecting transmission limits within the area. It uses 60 minute time steps for certain control decisions and 1 minute time steps to measure variability. The operational model considers the effects of variability as well as forecast errors, by using 3 forecast types.

The results indicate that increases in wind will degrade the CPS2 performance unless the amount of regulation used is increased. Montana currently procures 85 MW of regulation. The expected future regulation requirements ranged from 100 percent-384 percent of the current regulation requirements. No costs are calculated.

#### **4.9 Eastern Wind Integration and Transmission Study – January 2010 [12]**

The Eastern Wind Integration and Transmission Study (EWITS) study looks at the eastern interconnection in the US. The eastern connection is the largest system considered with a system peak load as studied is 530 GW. The study considers four transmission scenarios that are primarily made up of ultra-high voltage lines from Midwest to the Northeast. The four scenarios consider three different 20 percent penetration build outs and one 30 percent penetration in the year 2024. The 20 percent wind scenarios consider different utilizations of resources one considers high capacity factor; another considers local resources, and a third to consider more off shore development. The study uses three base years; 2004 through 2006 for the input data sets. These scenarios are compared to a reference case that includes current development and some near term development.

The primary analysis uses a production cost model to evaluate the impacts for each of the scenarios. The study also performs a variety of statistical analyses. EWITS uses statistical analysis to determine future reserve requirements. The production cost model makes use of the reserve requirement determination for its analysis. The study aggregates the balancing areas within the eastern connection into seven areas for 2024. The production cost models analyze the need for transmission as well as operating issues that occur.

The results show that 20 percent and 30 percent wind energy penetrations are possible in the eastern interconnection but will require significant new transmission. Substantial curtailment of wind would be required without new transmission, so much so that all cases will require some amount of new transmission. The study calculates wind integration costs that include transmission, and wind capital costs as well as operating changes costs. Production costs decline with increased wind penetration, though overall wind integration costs increase with penetration due largely to capital costs of transmission and wind generation. Very high increases in regulation will be needed. The regulation changes are calculated for each of the

balancing areas individually, regulation increases of over 1000 percent in some areas. Integration costs range from \$5.00 -6.68/MWh wind production. The carbon emissions are reduced roughly 4.5 percent for the 20 percent scenarios, and 18.83 percent from the 30 percent scenario, carbon sensitivities showed further reductions in emissions are possible (\$100/ton, 32.62 percent reduction on scenario 2).

#### **4.10 Nebraska Statewide Wind Integration Study – March 2010 [13]**

Initiated by the Nebraska Power Association representing the entire state of Nebraska, the study looks at a 2018 timeframe with three different wind energy penetration levels. The levels are 10 percent, 20 percent, and 40 percent. The 20 percent study has two sensitivities considering a case with additional extra high voltage transmission build out and a case without. The majority of the Nebraska system is in the eastern connection and is the primary focus of the study. A separation section evaluates western Nebraska which is part of the western interconnection. The study assumed the expected transmission system that is planned through 2013 would be available. Some additional extra high voltage transmission is modeled in one 20 percent case and the 40 percent case. The study uses the same wind generation data set as the eastern wind integration and transmission study, though particular site selections and build out may have varied. Wind capacity build outs for the different cases are 1,249MW, 2,488MW, and 4,727MW, each build out has a 41 percent capacity factor.

The study used both statistical and operational models. The main operational analysis uses an hourly production cost simulation model. The Nebraska study includes wind additions in the rest of the SPP as well as other areas of the eastern inter connection, the SPP build outs are changed for the different scenarios, though the broader eastern build out was static. Nebraska is studied in context with Southwest Power Pool (SPP). The study evaluates the reserve requirement variations with different amounts of wind generation. It also evaluates the system cost changes for the different wind penetrations. The study evaluates the emissions changes in the system.

The study finds wind curtailment in Nebraska isn't necessary for any of the scenarios, but occurs in the rest of the SPP in all scenarios except the 20 percent with high voltage grid overlay. Higher wind energy penetrations in Nebraska led to higher power exports. This suggests that the external system has greater flexibility in handling the additional wind power. The study predicts significant increases in regulation requirements, increases of 500MW, 1000MW, and 2000MW on average for the three cases. This increase is in comparison to the 300MW regulation requirement without the wind generation. Sharing can help reduce requirements. The study looks at the CO2 emissions and finds that Nebraska emissions decrease 8 percent between the 10 percent wind and 40 percent wind cases. Increasing penalty prices on CO2 emission reduced emissions between 2 percent and 19 percent. Combined cycle generation increases as CO2 emissions decrease. Overall the methodologies concluded that integration costs would be relatively small, between \$1.39/MWh wind and \$3.21/MWh for the 10 percent case.

The western part of Nebraska is in the WECC, and a separate study is performed. The western study has a different and more limited scope. It studies the addition of 300MW of wind generation. It considers the system's ability to handle this wind with the current transmission. Based on the 2008 system, western Nebraska could handle 50MW of wind and \$16 million investment would be necessary to interconnect 300 MW of wind capacity.

#### **4.11 Western Wind and Solar Integration Project – April 2010 [14]**

The Western Wind and Solar Integration (WWSIS) project focuses on the operational impacts of up to 35 percent energy penetration of wind, and solar generation on the power system operated by the WestConnect group. The WestConnect planning area is a group of several transmission providers in the WECC, covering Nevada, Arizona, New Mexico, Colorado, and Wyoming. The study looks at several scenarios ranging from 11 percent to 35 percent renewable energy penetration. Three wind energy penetrations within the west connect region are evaluated 10 percent, 20 percent, and 30 percent. An additional case of the 20 percent scenario is done with 20 percent wind penetration in the rest of the WECC region. These scenarios are compared with a preselected case made up of the installations that are online as of the end of 2008. The study uses data from the years 2004 through 2006 as the base data. The wind data modeled over 960 GW of wind sites across the western interconnection. The study also evaluates geographic sensitivities for the 30 percent case, looking at tradeoffs between build outs that were closer to load but lower capacity factor, or higher capacity factor but required long distance transmission. Three geographic scenarios are considered, one focusing heavily on local resources for each of the balancing areas and no new transmission projects, one focusing on the building out the best resources along with significant transmission, and one halfway in between.

The study performs four primary analyses. A statistical analysis quantifies the variability of the grid due to the load, and the changes with additional renewable. A production cost simulation analysis which evaluates hour-by-hour grid operations and had several outputs ranging from changes to generator commitment and dispatch, to operating costs, to emissions impacts. Additionally a minute to minute simulation investigates system ramping in more detail than the production simulations for a few selected days. Finally a resource adequacy study considers the generation resource mix necessary to maintain reliability. The four analyses together provide a very comprehensive set of impacts. They are able to assess many possible mitigation strategies such as forecasts, demand response, intra-hour scheduling and cooperation between balancing areas.

Overall the study shows that reliable operation of the power grid is possible even at the highest penetrations. The sub hourly analysis shows that inter-hour schedule changes make up the bulk of the system variability. The generation shift between hourly scheduling blocks is larger than the wind variability. The study shows that forecasting has a very large impact on the operating cost of the system, a state of the art forecast saves \$1-5 Billion per year, and a perfect forecast could save an additional \$100-500 Million per year. This is the single biggest impact on the system. With perfect forecast there are no contingency reserve shortfalls, though the 30 percent case experiences shortfall 89 hours a year when forecast error was present. Demand

response is the most economical way to eliminate the shortfall. Further cooperation between balancing areas can further reduce operating costs the reduction in reserves can save the WECC roughly \$2 Billion per year. Sub hourly scheduling is also critical, large increases of reserves will be needed unless interchange adjustments can be made more frequently than hourly. Sub hourly scheduling could cut the maneuvering of combined cycle units in half for the 30 percent case. Storage is unlikely to be economically supported by the addition of renewable generation. Operational flexibility is important for all generation. Renewable generation could be used to provide regulation down, additional hydro flexibility could save \$200 Million per year in the 30 percent case, and increased flexibility in coal plants could have a \$160 Million per year impact on system costs.

## CHAPTER 5:

# Results Comparison

The results of integration studies are one of the most important parts. The results are the basis for conclusions of the study and will determine if a study can meet its goals. The results of integration studies can vary significantly. The results vary due to the system, operation practices, and study methodology. The results can be expressed many different ways which can make direct comparisons difficult. Costs are the primary result from many studies. Some studies also go to great lengths to express all their results in terms of costs. On the other hand some studies do not consider integration costs at all. The results can also be expressed as an absolute or relative value. If they are expressed relative to a baseline it is important to understand what the baseline is. There are two common baselines that studies will compare to; one is the current system and the other is the system the same year as the wind scenario being studied but without the wind generation.

### 5.1 Variability

One of the first analyses in many wind integration studies is the variability in the system. Variability can come from a few sources. The load is a source of variability that system operators are accustomed to dealing with. It has variability across all timescales and is well studied. The generation is another source of variability; generators may not always follow instructions, or may have emergencies which suddenly change their output. The wind is the third source of variability and is considered separately from other generation because it behaves differently. The wind variability from wind generation increases with the amount of wind generation but there are other factors that are also important.

The timescale of the variability is often analyzed using one minute data up to 15 minute data. The magnitudes of variability increase with larger time frames. Consequently the ability of the system to adjust to changes also increases with larger time frames. The increases in variability are not linear with time interval though. For example in the Montana study the 97.5 percent percentile change on the 10 minute time scale is roughly 4 times greater than the changes on the 1-minute time scale across all penetrations. The ERCOT study has similar findings to the Montana study. It examines the variability of the net load for one minute and five minute periods. The study finds the standard deviation of the one minute net load increases about 5 percent for each 5 GW of wind capacity that is added. The standard deviations range from 43.2MW/minute to 49.7 MW/minute. The five minute variability follows a similar pattern. The standard deviation of the five minute variability is not five times greater than the one minute variability. It ranges from 167MW/5-minute to 197 MW/5-minute. The Arizona study shows that the majority of changes are small for wind generation. They find changes greater than 10 percent of capacity occur less than 1 percent of the time on 10 minute and hourly time scales.

Some studies perform statistical analysis on longer term changes such as the hourly average changes, or the changes across several hours. These larger statistical changes are particularly suited towards wind regimes with distinctive and repeatable diurnal patterns. California

exhibits these patterns and the CAISO report and the CEC IAP report both perform analysis on longer timeframes. The ERCOT study also considers the variability over longer time frames. An analysis of the hourly variability shows similar results to the shorter timescales. The standard deviation of the hourly variability increases between 6 percent and 18 percent depending on penetration. The variability of the hourly net load is not twelve times greater than the five minute variability.

The timing of the variability is another factor that studies will consider. The wind generation is often stable so understanding when it is likely to be more variable can help system operators greatly. The time of day can have a large effect on the magnitude of variability. This is especially true for areas that exhibit strong diurnal patterns. Variability is likely to follow similar patterns as the average generation. Another factor that can affect the variability of wind generation is the season. Different seasons have different weather patterns which can result in different amounts of wind generation on average. They also produce weather patterns that lead to different amounts of variability. The seasonal aspect is important as it corresponds to load patterns. Additional variability when the system is already stressed can have greater impacts than if the system has spare capacity available.

The variability is also studied with different amounts of wind diversity. Wind generation spread in different wind resource areas will face different weather patterns and is likely to be less variable than generation concentrated in one region. This means that some amount of variability may cancel out between different areas. It also means that the extreme changes are not likely to occur at the same time. The ERCOT study considers how the diversity of the wind generation can influence the variability. The ERCOT study considers two 10 GW wind generation build outs, with 1.5 GW of capacity diversified in one case. The variability in the more diverse case increases roughly 2 percent less than the less diverse case compared to the variability of load alone.

WWSIS considers the area to area variability to understand the effects of having diversity in the system. The study examines how the variability grows with wind penetration for each of the balancing areas individually and for them aggregated together. The study shows that the smaller balancing areas experience larger relative increases in variability with the same penetration of wind generation. The larger the area considered the smaller the increase in variability for the same wind penetration. Another important aspect is that the extreme changes in wind generation are not simultaneous across the footprint. The footprints coincidental extreme changes are about 45 percent of the sum of the extremes from the individual areas. This suggests that diversity and aggregation of wind resources is very beneficial to the power system.

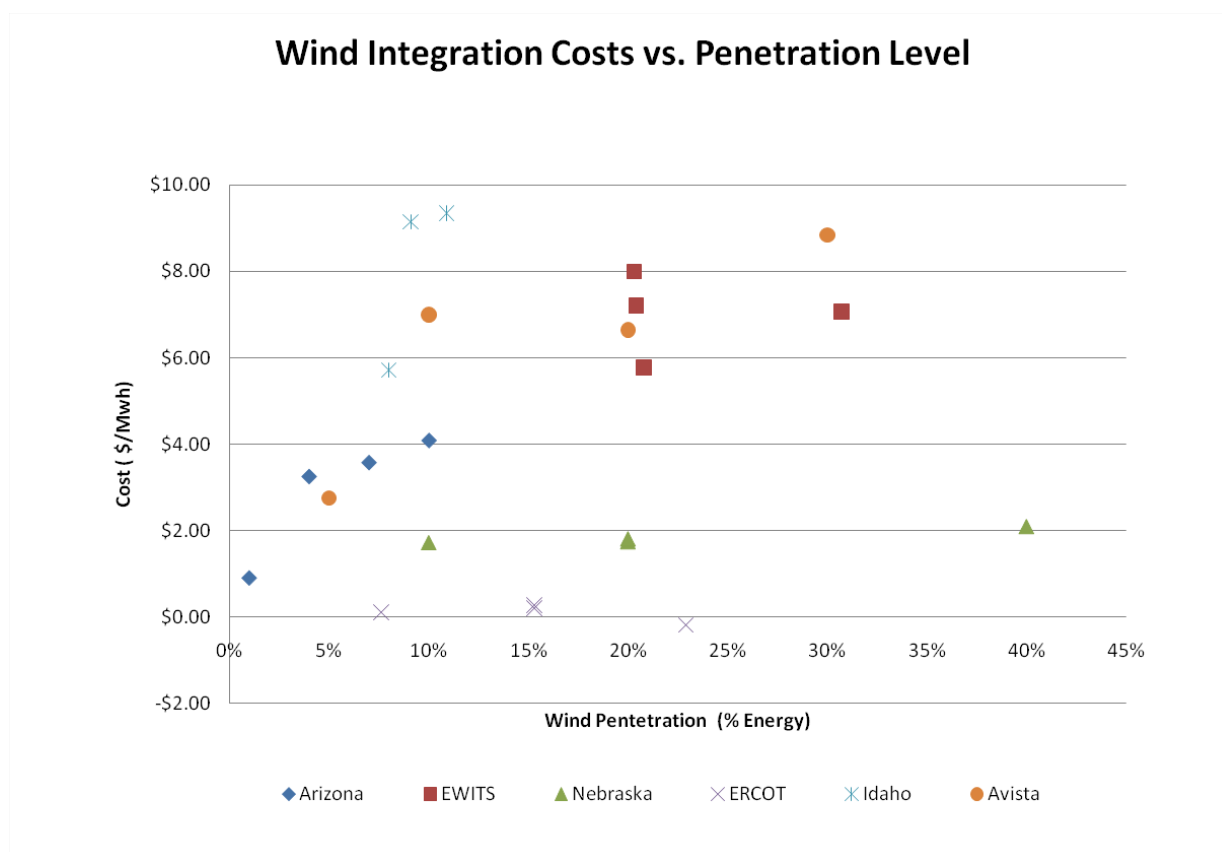
## **5.2 Costs**

The integration costs of wind generation are one of the key drivers to perform wind integration studies. For many wind integration studies determining the costs is the primary goal. Wind energy can impact different cost in a number of ways. There are capital costs for the generation and transmission and then there are production costs. The capital costs are often compared

against natural gas fired combined cycle or combustion turbine build outs with the same expectation of reliability. Production costs are made up of a number of different elements many studies attempt to break production costs up into some of their individual elements. There are fuel costs, operating costs, maintenance costs, congestion costs, transmission loss costs, ancillary service costs, and so forth. Wind generation has zero fuel cost but does have operations and maintenance costs. Wind generation displaces other resource which often saves fuel costs. The variability of wind generation could increase the flexibility needed in the system either through regulation or load following which will affect the production costs. The forecast uncertainty can have an impact on system costs. The changes in unit commitment will affect the operating costs by leading to sub-optimal unit commitment and dispatch.

Wince wind generation will affect the system costs in a variety of different ways there are many ways that studies attempt to quantify them. Studies that make use of production cost simulation models or hydro optimization models will get cost information was one of the results. The underlying assumptions can also have a huge impact on the integration costs. The costs for those models can include or exclude a number of features, for example if generation is paid its startup costs. Costs are also highly dependent on the physical system. For example the fuel costs for generation and the makeup of the fleet. The size of the system and strength of interconnection are other important factors. Smaller control areas tend to have higher integration costs, as do control area with less flexible resource mix. The costs of the studies are often calculated per MWh of energy generated by the wind. Figure 4 shows some costs for selected studies. There is a trend towards costs increasing with price, but that does not bear out in all cases. The overall integration costs are not directly comparable due to the differences in the methodologies for determining costs.

Figure 4: Integration Costs



One important factor that is related to cost is price. Prices will be influenced by the additional wind generation. The production cost models take this into account and calculate prices to get costs, though some other models do not consider the influence of the wind on the price. The integration costs in those cases may be based on unrealistic price. Wind generation is displacing other generation which should lower the prices of energy. Actual cost increases from no wind cases to wind build outs are typically driven by the transmission and capital costs of wind turbines.

The Avista study is a good example of determining integration costs. The Avista study provides very detailed cost results detailing which of the factors are driving the costs. The Avista system is a relatively small hydro dominated system. Their initial analysis breaks down the wind integration cost components due to the value of the wind, regulation, load following, and forecast error. Furthermore the Avista study looked at various sensitivities to identify the impacts some operating changes can have. The overall costs for Avista range from \$2.75/MWh to \$8.84/MWh. One cost that stands out for the Avista study is the cost of diversity. The Avista study considers the same four penetrations with five different build outs. The wind integration costs are calculated for each combination. The scenario with the most diversity has the lowest

costs at all penetrations. At the highest penetrations the least diverse case has integration costs about 2.5 times higher than the most diverse case.

The ERCOT study has very interesting cost results. Overall the study predicts very modest integration costs, less than \$1/MWh even with 25 percent penetration. The ERCOT costs take a very limited view of the costs compared with the other studies. The costs represent the additional regulation reserves that are procured to balance the system with the extra wind generation. The marginal price of the reserves actually goes down compared to the no wind case. The price drops because the wind generation offsets conventional generation which is then available to provide reserves instead of energy. In this case the supply of reserves increases more than the demand for reserves does, leading to a small decline in marginal price, but a total cost increase due to a higher provision of reserve.

The Idaho study has some of the highest integration costs; this is driven by a few factors. One factor is the Idaho is a relatively small control area with limited flexibility. Another factor is the Idaho model uses historic prices, which included the California energy crises which impacted prices throughout the western US, driving up price significantly. The Idaho study was revised with different prices from 2006 which are more representative of typical system performance. Even with the adjustment Idaho has the highest integration costs. One possible reason for the Idaho studies costs is that the prices are inputs. While the typical production cost model produces prices as an output, this means that the extra supply of the wind generation studied does not help reduce the prices of energy or ancillary services. The Idaho model is also specialized to consider changes to the hydro system primarily. Wind integration costs in the Idaho study are up to \$9.35 /MWh for an 11 percent energy penetration.

The EWITS study is an interesting example of high integration costs. The EWITS study has three cases at 20 percent representing different build outs of wind power, some more diverse than others. The EWITS study also represents the largest geographic footprint, and the highest electricity usage of the studies. The costs ranged between \$6-8/MWh. The highest cost is actually associated with a 20 percent energy penetration case and not the 33 percent case. This suggests that there is more than just energy penetration that will determine system costs. The uncertainty and variability of wind that is often a large concern may not be driving the costs. The EWITS study included capital costs, operating costs and production costs in its overall cost calculation. This is more inclusive than many other studies that typically only include production costs. The inclusion of capital costs is one of the main drivers of the overall costs, and also helps to explain the high costs. One would expect modest integration costs in an area as large and diverse as the eastern interconnection. The large area necessitates significant transmission investment to transfer the wind energy throughout the interconnection.

### **5.3 Energy Displacement and Unit Commitment**

One of the results from a production cost simulation is the amount of energy derived from different types of generation. The resource mix is usually looked at in terms of energy displacement. The energy from different resource types is compared with and without wind generation to see how patterns change with wind generation. The displacement of generation is

important to consider because it can affect the system's ability to respond to events. Displacement of resources is largely driven by the resource mix in an area. Typically base load units are the least affected and only dispatched during highest penetration periods. Unit commitment changes go along with the energy changes. Units that are not committed due to increased wind generation will not be online to provide energy and will have much lower contributions. If wind generation is being used for RPS purposes but displaces other renewable generation it may not provide the desired benefits. The instantaneous penetration of wind power can become an extremely important factor. Wind generally is not certified to provide ancillary services. At high instances wind penetration levels generation may be kept online at minimum generation to provide ancillary services.

The ERCOT study shows that the energy from combined cycle units is offset the most by additional wind generation. Energy from coal is also slightly reduced. It is interesting that energy from gas turbines increases except for the highest penetration of wind generation. This is likely because of the flexibility that gas turbines have they are able to respond quickly to make up for variability and uncertainty. Similar studies have similar results; the resources displaced are largely a factor of the system configuration. Though increased wind generation tends to displace the most expensive units.

EWITS has some very interesting results for how the wind impacts the energy from different sources. The study shows that having different amounts of forecast error can affect the energy from different sources. Increasing forecast error cause energy to shift from less flexible sources such as coal to more flexible sources such as combined cycle and gas turbines. Reductions in coal energy were in the range of 3 percent-4 percent for the cases with forecast versus the perfect forecast cases. Meanwhile combined cycle generation increases roughly 20 percent, and energy from gas turbines increase 20 percent-30 percent. It should be noted that coal energy is roughly 15 times that of combined cycle, while gas turbine energy is roughly 25 percent of the combined cycle generation.

## **5.4 Reserve Requirements**

Determining proper levels of ancillary service or reserves required with different wind penetrations is also one of the main concerns addressed in each study. There are two concerns with reserves; how much reserves is needed and does the system have the capability to provide them. The system's ability to provide reserves will also depend on the displacement of other generation. If the uncertainty and variability of wind generation is significant reserves could increase beyond the system's ability to provide them. System planning will likely need to take into account the ability to provide reserves as well as energy. Regulation is the most impacted reserve requirement. Regulation is also the most expensive reserve as it is the most flexible. Spinning reserve could be affected if the wind was concentrated and represented a credible contingency. Some systems also carry a replacement reserve product, which could be dispatched either in a contingency or if there are significant schedule deviations. These other reserves can also be affected.

Determining regulation reserves requirements varies significantly between the studies. Some studies rely on statistical techniques to estimate the regulation, while others use the operational models. One factor that can influence the regulation results significantly is the extent to which short term forecasts are modeled. The ERCOT study is a good example of this. ERCOT uses 1 minute steps of the net load compared to the 5 minute dispatch point (the first point of the 5 minute period). This implicitly assumes that the short term forecast used to do the dispatch is 100 percent accurate. In practice there would be some uncertainty in the forecast, the additional uncertainty would also need to be met by regulation. This could lead the study to the relatively modest increases in regulation it predicts, 15-50MW, with 5000-15000MW wind capacity installed. ERCOT normally maintains about 230MW of regulation. The CEC IAP study, also performed by GE, uses a similar technique for calculating regulation requirements. It determines similar additional regulation requirements of about 20MW on 7.5 GW of wind capacity.

In contrast to the ERCOT and CEC IAP studies are the Montana and CAISO studies. The CAISO study relies on the data from the CEC IAP study, yet the methodology was significantly different. Both Montana and CAISO employ techniques to measure the regulation requirements based on the expected system needs caused both from the variability of the wind power and from the uncertainty in the short term forecasts. This is in contrast to some of the other studies whose methodologies implicitly assumed perfect forecasts in the short term, and therefore measured only the variability components. The CAISO study estimates that regulation with 7GW wind capacity would need to increase by 100-500MW depending on the hour and season to maintain the same performance. California normally maintains 350MW of regulation. The Montana study estimates a 0-241 MW increase in regulation needs, on up to 1450MW wind addition. This results in 1-3.84 fold increase in the procurement of regulation.

The EWITS study regulation methodology is a hybrid of some of the other regulation methodologies discussed in this section. The EWITS study does a statistical analysis for the regulation component. It makes several assumptions to estimate the order of magnitude of the regulation that is needed due to variability. The study finds that the regulation due to variability alone is small, roughly 25MW, and it does not need to be considered in more detail. The study then does an analysis of short term forecast performance based on a simple persistence model with a 10-minute lead time. From the short term uncertainty analysis it determines a substantial increase in regulation can be needed for wind power, 800MW regulation for some of the larger areas. The Nebraska study also has large additional reserves, using a similar methodology to EWITS. Its regulation requirements for Nebraska Power Authority and SPP areas together increase by around 500MW at 10 percent wind energy, 20 percent wind energy increases incremental amount to about 1000MW, and about 2000MW at 40 percent penetration.

## **5.5 Load Following and Ramping**

Load following is another aspect that is often considered with wind integration. Load following is fairly loosely defined and it can vary quite a bit between different regions. Generally speaking load following is the dispatch of generation necessary to keep the system balanced. Load following is measured as the difference between the forward schedule of generation and

the dispatch. It has typically been used to make up for load forecast errors, and for the natural differences that occur when scheduling is done on hourly blocks. Using regulation for these larger and longer term changes is expensive.

Ramping is closely related to load following. Most systems will have peak load in the day and minimum load at night. In order to match the load the generation in the system ramps up in the morning as the load rises to the peak. Then it ramps down in the evening towards the minimum load. The magnitude, rate, and duration of these ramps are important to keeping the system balanced. The generation on the system must have sufficient flexibility to meet the demands of the ramps on a system wide basis. Wind generation has the ability to affect the perceived ramp the system sees. Generation must be able to follow the net ramp on the system. In many regions wind has a diurnal pattern that is out of phase with load. Wind generation will peak at night and be at a minimum during the day. This has the effect of increasing the needed ramping as other generation is used to balance the wind.

The CAISO study shows lots of analysis relating to the load following and ramping concerns. The study uses both statistical and operational models to address the concerns. The study uses a statistical model to consider the potential impacts of wind generation on the morning and evening ramps. The methodology is designed to look at extreme ramps that may potentially occur. The data is separated into different seasons and the maximum seasonal ramps are calculated for load alone, and for load minus wind. The CAISO does an analysis examining the expected maximum net load ramps during the shoulder hours, or the hours of the morning when load rises rapidly and the hours in the evening when it declines. The CAISO study shows that the maximum net ramp could increase over 30 percent from the baseline values. Their analysis represents the extreme combination for each season, and is boosted by the consistent diurnal pattern of wind generation which is opposite the load shape. The WWSIS uses a similar analysis and shows that the largest net ramp increases 50 percent from the baseline at the 30 percent penetration level.

The CAISO load following methodology is an operational model that considers short term dispatch for a simplified system, considering the net load changes and short term forecast error. The load following study estimates that the amount of load following increase roughly 800MW from a base of 2200MW. A sensitivity analysis is performed with a modest decrease in forecast error. The sensitivity shows forecasts improvements can reduce the additional load following requirement by about 50 percent.

## **5.6 Transmission and Reliability**

Strong wind resources are often located far from population centers that consume the bulk of the electricity. Transmission is required to move the energy to where it will be used.

Transmission can be one of the most expensive components of integrating wind. Older wind integration studies focused a great deal on the transmission design to accommodate wind. The need for transmission analysis in a wind integration study has diminished due to the lessons learned from previous studies and the new technology in wind turbines that eliminates some problems. Transmission is important for wind integration even if it no longer a prominent

focus. The primary transmission considerations for wind resources are sizing, voltage regulation, reactive capability, grid disturbances, control, and frequency response. [15]

There are a few reasons that design of transmission facilities takes a different approach when it comes to integrating wind generation. Transmission facilities include not only transmission lines, but also transformers, capacitors and other hardware. The intermittent nature of wind is one concern. Wind generates below its rated power most of the time so lines may not need to be sized for full delivery. Another issue with transmission design is the location of wind resources. Strong wind resource areas are often located far from load centers in weak areas of the power grid. Transmission lines for wind may be trunk lines that connect radial to the power grid, which would not have alternate routes in case of outage.

More recent integration studies haven't emphasized the transmission component as much as in the past. Assumptions are that transmission will be built or upgraded as necessary to accommodate the new wind generation, and that the changes in operating characteristics are more important to focus on. Each new facility when built will be subject to a transmission study, which will determine in detail the needed transmission and the expected impacts. The studies that have included some transmission analysis have shown that new transmission is useful and sometimes necessary. One interesting thing is that extra high voltage<sup>11</sup> transmission lines are often called for in relation to wind.

The electrical generator characteristics of wind generation also differ from conventional generation. Conventional generators use permanent magnet generators which operate at fixed speeds to produce power. Permanent magnet generators provide inertia for the grid; the electro-mechanical link helps resist changes in system frequency. Wind generation however has used induction generators (IG). Modern turbines use more advanced doubly fed induction generators (DFIG) instead of standard IGs. DFIGs are variable speed generators allowing the generators to operate more efficiently over a wider range of wind speeds. Also DFIG generators can control the amount reactive power used or supplied much like a traditional generator. Another common generator for a modern turbine is a full conversion system. With a full conversion system the generator generates an AC power which is converted to a DC and then back to grid synchronized AC power. The AC-DC-AC systems have the benefits of the DFIG system over the standard IG and are capable of providing inertial response. These new turbine generator systems have alleviated much of the worry with respect to the electrical connection. [15, 25]

Fault tolerance was another area of concern for wind generation on the transmission system. Older wind turbine generators were not fault tolerant and often dropped off line during grid disturbances. Operators encouraged this performance in the past for small amounts of wind, because the grid would drop a small amount of generation that could be easily replaced. As wind penetrations increase the potential disruptions from all the wind dropping is of large concern. Grid codes in many areas now require wind generation to have low voltage ride

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<sup>11</sup> Lines above 500kV

through, LVRT, capability. This has been a feature on modern wind turbines for several years. It can also be done on older turbines through electrical components at the grid connection.

Voltage regulation is another concern for wind generation. The concern is related to the characteristics of IG. In order to generate IG consumes reactive power this affects the local voltage. Wind generation has evolved beyond simple IG to doubly fed induction generation, DFIG, and full AC-DC-AC conversion. These new generators do not use reactive power the way older models did and are able to support voltage; many of these generators can even help support voltage when there is insufficient wind to generate power. Supporting the local voltage is important for generation particularly if there is no other generation in the area.

Frequency response or inertial response is another area of concern when integrating wind in the power system. When a large fault happens the system becomes suddenly imbalanced, the frequency changes as a result. The large amount of rotating mass behind generators helps arrest the frequency changes keeping it in a manageable range as the system is rebalanced. Some wind generators do not provide inertia this way due to the generator types. If large amounts of wind replace conventional generation care will need to be taken to make sure that frequency changes will be manageable. Conventional generator can also have frequency responsive governors, which are able to provide an injection of power if frequency dips suddenly to counteract the change. Since wind generation attempts to make maximum use of the available wind it may not be able to respond to frequency dips. If wind has displaced significant conventional generation, there is concern that a frequency dip may not be arrested, which could cause a cascading blackout as generators shut down to avoid damage that is caused by generating under frequency. This is still an area of investigation as national standards are developing for frequency response initiatives. Modern wind turbines do have some ability to provide inertial response.

Modern supervisory control and data acquisition systems (SCADA) have also helped improved integration. Modern SCADA systems allow real time detail measurements of wind plants to be visible to operators. Additionally they allow wind plants to control their output, while historically they would be subject only to the weather. SCADA systems combined with improvements in wind generators can help eliminate many of the transmission and reliability concerns associated with large penetrations of wind power.

## **5.7 Emissions**

Emissions impacts are a key point of concern for several studies. The electric power sector has had emissions regulations for many years. Nitrous Oxides (NO<sub>x</sub>) and Sulfur Oxides (SO<sub>x</sub>) are currently regulated nationwide as they are the primary causes of smog and acid rain. Carbon dioxide (CO<sub>2</sub>) regulations are being enacted or considered in many areas. CO<sub>2</sub> emissions are the primary concern in most integration studies. Emission impacts are generally studied through the use of the production cost models. These models contain the heat rates of the conventional generation, which are converted into an emissions level. In addition many production cost models offer the ability to constrain or price emissions direct, making emissions

an explicit factor in the optimization. This allows modelers to include existing regulations, or to test impacts of new regulations.

The emissions generally are reduced with increased wind generation. The primary mechanism is wind generation displacing fossil fuel generation. The amount of emissions reductions will depend on the wind penetration and the generation makeup of the system. There are some complexities to consider if wind on its own is the best way to reduce emissions. If wind is displacing low emissions resources it is unlikely to achieve substantial emissions reductions. Furthermore the wind could change the dispatch levels of other generation to a less efficient operating range. While the emissions will still be lowered, some of the reductions will be offset by operating less efficiently. Because of these factors the emissions reductions vary significantly between the different studies.

The Nebraska study considers what happens to CO<sub>2</sub> emissions as wind is added as well as if a CO<sub>2</sub> price is added. Without the CO<sub>2</sub> prices Nebraska expects a CO<sub>2</sub> emissions reduction of 8 percent going from the 10 percent wind case to the 40 percent case. Three CO<sub>2</sub> prices are tested \$25, \$50, \$120/short ton. Adding CO<sub>2</sub> prices reduces the amount of CO<sub>2</sub> emission relative to cases without CO<sub>2</sub> prices. The reductions are modest, the \$25 case reduces CO<sub>2</sub> by about 2 percent, \$50 by 6 percent, and \$120 by 19 percent from the case without CO<sub>2</sub> prices. The CO<sub>2</sub> reductions are achieved largely from replacing coal generation with natural gas generation. Combined cycle use increases 138 percent from the \$25 case to the \$120 case. This is because the additional price paid for carbon emissions serves to reduce the fuel price differential between gas and coal.

The EWITS study also does some includes interesting emissions analysis. The study performs a sensitivity of one scenario with an added \$100/ton carbon price to the model. This has significant effects on the results obtained. The added wind reduces carbon emissions by about 5 percent from the 2008 base case, even though the study case models the year 2024 with significantly more load. Adding a carbon price with the wind generation causes the carbon emissions to be reduced by 32 percent from the 2008 base case. The changes in emissions are the result of changing the energy sources. Adding carbon prices decreases the amount of power from coal fired plants, and increases power from nuclear and natural gas plants. The carbon price also impacts the amount of wind curtailment. The curtailment was reduced from 6.79 percent in the original case, to 5.47 percent in the carbon sensitivity case. There are significant costs associated with the carbon sensitivity. The production costs see a very large increase over the original case.

The WWSIS study examines the emissions impacts that renewable generation has on the system. Unlike other studies it considers effects for NO<sub>x</sub> and SO<sub>x</sub> in addition to CO<sub>2</sub>. WWSIS uses a fixed carbon price of \$30/ton CO<sub>2</sub> in the production cost model. The study examines how fuel prices will affect the emissions. The study uses \$2/MBTU coal, and \$9.50/MBTU gas, \$30/ton CO<sub>2</sub> as the base case with a sensitivity that drops the natural gas price to \$3.50/MBTU gas. This makes electricity from coal and natural gas much more competitive. In the first case the additional wind generation drops CO<sub>2</sub> emissions by 25 percent, Sox by 5 percent, and NO<sub>x</sub> by 15 percent. Lowering the price of natural gas results in even further emissions reductions; a

45 percent reduction for CO<sub>2</sub>, 50 percent for NO<sub>x</sub>, and 30 percent for SO<sub>x</sub>. In the normal case wind generation primarily displaces the natural gas generation which is less economical than coal. This could have other side effects when integrating variable generation since natural gas generation is typically much more flexible than coal. When the price of natural gas is reduced making it competitive with coal, coal generation is primarily displaced. This has the benefit of further reducing emissions as well as having more flexible generation online.

## CHAPTER 6:

# Study Recommendations

The results of integration studies lead to a series of recommendations for integrating wind generation. Despite many differences in operations, penetration levels, resource mixes, area size some recommendations are near universal. Many of the recommendations are for specific policies and practices to be adopted as the wind penetrations increase to mitigate problems. Studies also frequently recommend additional studies to provide greater understanding of wind generation. Some of the recommended studies would be necessary to implement the policy recommendations. Some of the recommendations directly follow from the results. In some cases the effectiveness of different practices are tested by the methodologies. There are three basic strategies for managing wind integration; reduce uncertainty, increase flexibility, and increase diversity.

### 6.1 Managing Impacts

Having studied the expected impacts of wind integration studies suggests ways to manage those impacts. There are a wide range of operations changes that are suggested to help manage large penetrations of wind energy. The recommendations tend to address the operating practices that can impact wind. Many of the suggestions are studied as part of the analysis to determine how effective they can be.

#### 6.1.1 Forecasting

Wind forecasting is seen as one of the best ways to reliably accommodate wind power. Forecasts directly affect the uncertainty, which can be a larger challenge than the variability. ERCOT and EWITS for example show the uncertainty of wind generation to be greater than the variability. Many studies explicitly included forecast model in the analysis which indicates the importance. There have been some studies specifically looking at forecasting specifically, most notable the Alberta forecasting pilot project, and the CAISO PIRP RFB [22, 23, 24].

The majority of the studies suggest using a centralized forecasting service which the grid operator will use to make operating decisions. Centralized forecasting has several advantages over a decentralized system where every wind plant would provide their own forecasts. Centralized systems can make use of all the data from all farms. This not only allows for better forecasts due to availability of more measurements, but allows more fault tolerance if data at a particular site isn't available, a forecast could still be made with reasonable accuracy using data from neighboring sites. A centralized forecast also allows the system operator to seek the best forecast available for its purposes; wind plant operators may have other incentives.

There are several other decisions in forecast design that allow forecasts to be tuned for specific operating areas. The forecast horizon, time step, lead time, and update frequency are all important factors. Operators design forecasts to line up with the other operations processes. A day-ahead forecast for use in the unit commitment process and a short term forecast for dispatch is a common approach to forecasting. Additional consideration is done with respect to

how forecasts are optimized, how accuracy measured and maximized. A summary on current forecasting practices in North America can be found in [19]. Benefits of wind forecasting are quite significant, for example WWSIS estimates benefits \$1-5 billion per year.

### 6.1.2 Curtailment

Another very common operating practice to manage wind is to curtail the wind generation periodically. Due to the zero fuel cost of wind, it is generally desirable to use as much wind as possible offsetting resources with higher marginal costs. Curtailment is a way to add additional flexibility to system. Most studies show that benefits can be achieved by having limited curtailment. The periods when curtailment is most helpful are when load is low and wind is high; when transmission is constrained, or when wind forecasts have large errors. The EWITS study finds that wind curtailment can be an effective strategy to respect transmission limitations without having to do expensive upgrades. With modern wind turbine SCADA systems wind curtailment can easily be implemented. Many studies include the ability to curtail wind in their models, which gives an indication of the effectiveness that curtailment can provide.

The Avista study shows one method for valuing wind curtailment. Avista performs a sensitivity to determine the effects of wind curtailment on their system. The Avista base case allowed for wind production curtailment for reliability reasons as well as for economic reasons. For wind to be curtailed for economic reasons it is compensated for the energy payment lost as well as the value of PTC lost. The sensitivity run changes wind curtailment rules to be determined solely by reliability. The results show that the additional economic curtailment in the base case reduced energy from wind by 0.4 percent in the 5 percent case up to 1.4 percent in the 30 percent case. Avista also computes the wind integration costs in the sensitivity the same as the base case. The sensitivities which only allow curtailment for reliability regions increase costs over the base case. The cost increases range from 37 percent for the 5 percent wind case to roughly 20 percent for the 10 percent, 20 percent, and 30 percent cases. The results suggest that curtailment can be a very effective strategy; even if generators are compensated for lost revenue including PTC the cost savings on minimal amounts of curtailment can be quite significant.

The WWSIS study also looks into curtailment of wind energy. The WWSIS study is a good contrast because it is nearly 38 times larger in peak load than the Avista system. The WWSIS study shows that wind curtailment isn't necessary until wind exceeds 20 percent energy penetration. The study assumes that a state of the art forecast is used for the wind generation. The system has sufficient flexibility to adjust for forecast errors. As the wind penetration increases to 30 percent some curtailment is necessary. The hourly simulations indicate about 800 GWh of curtailment is necessary, or less than 0.5 percent of wind energy. The QSS simulations indicate that curtailment will be higher on the order of 1 percent of total wind energy. The amount of curtailment was also dependent on a number of other factors. A sensitivity is performed with restricted coal generation dispatch, this results in increased curtailment. This suggested that the flexibility of other generation is an important factor for wind curtailment.

Curtailment of wind generation can be an effective strategy to integrate high penetrations of wind generation. Wind curtailment is necessary very rarely. It can be triggered either for reliability or economic consideration. Wind curtailment can add a lot of flexibility to the power system increasing the control options available. The wind curtailment recommended in studies would displace a small amount of energy overall and could provide substantial benefits.

### 6.1.3 Adjust Scheduling and Dispatch

Scheduling practices vary widely between different balancing areas. The scheduling lead time and time steps are both very important when it comes to integrating wind generation. Many areas do the majority of scheduling well ahead of the operating hour and fix hourly schedules for most units. This puts them at a disadvantage when try to deal with forecast error and variability within an hour. Without a way to change dispatch or adjust schedules within an hour systems must use expensive regulation to keep the system in balance. Having a real time market, or a similar process to adjust schedules within the hour will help prevent flexibility from being stranded, and will reduce the amount of regulation needed. It will allow the flexibility of units to be realized through a more efficient dispatch process. Changing the dispatch process should allow ancillary services, primarily regulation to be reduced. Systems that operate markets on a five or ten minute basis have more flexibility to adjust to wind generation.

The Avista study models how the market structure can change the wind integration costs. The study considered adding a 10-minute market on top of the hourly market that exists. The study shows that between 45 percent and 75 percent of the integration costs are attributable to factors that occur within hour, meaning that most of the costs occur because the system is locked in for an hour. When the 10-minute market is added to the analysis it gives the system more flexibility to respond to conditions. For their system the integration costs are lowered between 40 percent and 60 percent with the addition of the 10-minute market.

### 6.1.4 Change Ancillary Services

The majority of studies show that the necessary amount of ancillary services will increase. Many studies focus on regulation, and suggest increasing the amount of regulation procured. The estimates of regulation increases vary significantly between the studies. Though there is a considerable range all studies agree that increasing wind generation will increase the amount of ancillary services a region maintains to keep the same reliability level. Regulation is the ancillary service most affected. Ancillary services are usually more expensive than energy and the system tries to keep the cost down. The variation in ancillary services relative needs between balancing areas depends in large part on the scheduling timeframes.

One way to offset increases in ancillary services is to increase the entities that can provide them. This includes having more generation certified to provide ancillary services, including wind generation. Wind generation is capable of providing a variety of ancillary services. While it is operational it could be used to provide down regulation by reducing its generation compared to what it could produce. Certain loads could also provide some additional ancillary services if needed.

Another option for systems other than simply increasing the regulation procured is develop ways to forecast the needed regulation. Most of the time wind generation is stable and does not contribute to the regulation needs of the system and it would be inefficient to procure more regulation than would be needed. If the increases of regulation correspond only to when it would be needed the overall impact will be lowered.

Some studies suggest new ancillary services, a dispatch-able reserve that is not as fast as regulation, but would still provide needed flexibility to the system. The new ancillary service product often falls into the load following range. It is thought of as a way of ensuring that sufficient load following will be available to the system operator to deal with variability and uncertainty within an operating hour. ERCOT discusses a reserve that is available in 10-15 minutes, while the CAISO study considers a 30 minute reserve product.

### 6.1.5 Encourage Flexible Generation

Operators are concerned about the increased variability in the system, as well as additional need for ancillary services. As a way of managing this operators suggest encouraging the development of more flexible generation. This includes constructing new generation that can meet future needs or retrofitting current generation to operate more flexibly. In order to encourage generators with sufficient flexibility to be constructed operators will need to compensate generators for the extra benefits they provide. One way to do this is to make resource adequacy payments that consider more than available capacity. There are several attributes that system operators consider when thinking about generator flexibility.

One way for generation to provide more flexibility is to become certified to provide ancillary services. This will give generation the flexibility to provide energy or ancillary services as need. Ancillary services themselves typically have specific requirements for generator maneuverability. Even if they are not providing ancillary services they will have the capability to respond.

Faster ramping is another way generation can be more flexible. The more rapidly a generator can adjust its output the more it can do to respond to the current needs of the system. Ramping capability increases will enable more load following per generator.

Minimum operating point is one important property for improving generation flexibility. A low minimum operating point will allow a generator to remain online during a wider range of conditions. Many generators need to remain online during minimum load periods for reliability concerns or because they cannot cycle quickly enough to come back when they will be needed. In these cases over generation can become a concern, especially if load drops below its forecast or wind generates more than its forecast. This is particularly useful for systems that expect the wind to be out of phase with the load.

Frequent cycling capability is another desirable feature. Generators that can cycle daily or more frequently are desirable. Faster start and stop capability goes along with frequent cycling. This refers to the amount of time it takes for a generator to turn on or off from when it receives an instruction. This amount of time can be one the order of days so reducing it to hours or less could greatly increase flexibility.

### 6.1.6 Demand Response

Demand response is a policy that is often discussed as a useful enhancement to the power grid. It refers to the ability of a system operator to adjust the load in the system. Since historically operators only had control of generation, they used generation to match the load. Adding the ability for some load to be controlled can take some strain off of the generation. Some demand response has been used to reduce the peak loads systems experience. Demand response will need to be expanded to allow more loads to choose to respond to economic signals. Trying to meet the variability of wind generation solely with generation can increase system cost significantly. Demand response stands on its own as a way to enhance the power system. Demand response can allow systems to avoid installing expensive peak generation that is rarely used.

### 6.1.7 Zoning and Aggregation

Many studies have shown there are benefits for increasing diversity of wind resources. Diverse wind resources aggregated together have a smaller amount of variability than one's close together. If systems can encourage wind generation in many areas they will have to make fewer changes to accommodate the wind.

Competitive renewable energy zones (CREZs) are one way to ease some of the integration concerns. CREZs are predefined geographic areas that have rich resources for renewable generation. Establishing CREZ allows for a study of a particular area as a whole and not relying on individual projects within that area. This will enable systems to appropriately design transmission to provide maximum benefit for an entire area and can simplify the planning process. CREZs can also help to increase diversity of wind resources. If appropriately designed they can allow for the aggregation of many different wind plants, this will reduce the apparent variability on the system and therefore reduce the amount of balancing that must be performed.

Another option for aggregation is a larger balancing area. Larger balancing areas reduce the penetration of wind generation which reduces the effects. Additionally larger balancing areas will have larger generation fleets and more flexibility in how they are dispatched. The EWITS study uses aggregated balancing areas for its baseline analysis.

### 6.1.8 Grid Codes

Reliability organizations are actively studying renewable energy and revising grid codes to ensure the reliability of the system. LVRT and reactive control are some of the standards that have been introduced. Balancing areas, reliability regions, and NERC will continue to review wind turbine technology and power system performance to assure that there will be the reliable operation of the power grid. Grid codes will ensure that wind won't harm the power systems reliability.

### 6.1.9 Telemetry

It is very important for system operators to have quality information on the state of the system. This will enable them to ensure the reliability. Telemetry of the power system elements is crucial to giving system operators the information they need. Telemetry at wind sites should provide both meteorological and power data. Real time measurement of wind plant

performance can have a variety of benefits. Power systems have real time monitoring systems which typically measure generation and transmission conditions. System operators continually monitor the conditions of the system and make operating decisions based off the measurements. These systems can be easily adapted to include wind production information as well as local meteorological information for wind farms. This information includes things such as wind speed, wind direction, air temperature, pressure, and humidity. The data can give operators real time information on the generation of wind, its variability, and recent trends. Measurements can also be used by forecasters to help better predict the wind generation. Telemetry for transmission elements should also be increased to monitor the greater system, especially for upgrades to integrate wind generation.

#### 6.1.10 Storage

Storage is often discussed in the integration studies and there are many possibilities for how storage could benefit a system with high penetrations of renewable. Energy storage has the potential to address both the intermittency of wind and the variability depending on characteristics of the storage. There are a wide variety of different storage technologies with a variety of different operating characteristics. The CAISO study describes many of the technologies and properties that they offer. The predominant technologies are pumped storage hydro, compressed air, batteries, flywheels, super capacitors, and hydrogen. The ability of storage to mitigate potential problems will depend on its characteristics. A large storage system would be able to charge during windy conditions if the energy isn't needed then and could then discharge when it is calm and more electricity is needed. To shift energy pumped storage hydro is the most practical storage type; many areas already have some pumped storage hydro installed. Smaller storage could be used to manage the variability principally within hour. Under the right conditions storage could contribute to a variety of operations functions. Storage could be used to provide reserves and regulation. It could be used for load following services. It could be used to provide peak power, or add demand in minimum load conditions. Storage could provide reactive support to the system or provide inertial response.

While storage has many potential benefits for power systems it is important to understand a few things about it. First, storage needs to make sense from the system perspective compared with other operational strategies. If wind does add variability to the system the systems needs should be evaluated relative to the variability, storage should not be used to return the system to its state before wind is added. Second is the cost and benefit analysis. Storage will be competing with other generation for all those possible functions and the revenue model for storage is often unclear. On the cost issue alone building storage is more expensive than equivalent capacity gas turbines. The EWITS study suggests that in certain situations storage can be used instead of transmission upgrades, though further study would be needed to determine the costs and benefits.

The WSSIS study has a good example of storage analysis. The system that is studied includes existing pumped storage hydro. The study finds that the usage of pumped storage increases as renewable penetrations increases. The study also performs some sensitivities looking to optimize the use of the storage. The results indicate that if there is perfect forecasting for

renewables the storage isn't needed even at higher penetrations. If there is forecast error storage could mitigate but the error isn't known ahead of time so pumped storage cannot be effectively scheduled. The study concludes that the economics will not justify new storage facilities. The study also considers storage for uses other than arbitrage. Storage for reserves, regulation and load following could be useful, especially if it would be available at times when the system does not have flexibility with the traditional generation. An economic study is suggested for this type of storage.

Nebraska looks at impacts on existing storage in context of wind with CO2 pricing. It finds that CO2 pricing lessens the peak and off peak price differential and makes storage less viable. Storage may still provide benefits but the current revenue model would not support it. The study also considers smaller short term storage but additional study would be necessary.

#### **6.1.11 Coordination**

System operators with a few notable exceptions are not alone in trying to maintain system reliability. Interconnections have dozens of control areas that need to interact to maintain reliability. Current practices typically lock in the flows between control areas in hourly blocks. More flexibility between balancing areas is seen as a way to increase the diversity in the system and mitigate wind generation. There are many ways for areas to coordinate their integration efforts. More frequent scheduling on shared line or connections is one. This allows greater flexibility within the areas if they do not have to maintain fixed flows across their interconnections for a full hour. Data sharing is another way areas can coordinate. Sharing of information about weather conditions can help areas coordinate their wind generation and perhaps get better forecasts. Coordination could mean consolidating balancing areas into large areas with one operator.

## **6.2 Future Study Recommendations**

Wind integration studies are designed with specific goals and do not address all possible aspects of wind integration. As studies are completed the results may identify areas where further study is suggested. Some of suggestions for future study are for areas intentionally neglected in the initial study. The areas of study often align closely with the recommendations to integrate wind. Commonly the recommendations to mitigate the wind will require further study to implement. Areas with a lot of uncertainty such as development of new technology also warrant future study.

### **6.2.1 Subhourly Studies**

Sub-hourly operational studies are often suggested to make up for deficiencies with production cost models that are limited to one hour scheduling blocks. Sub-hourly studies are present in many of the integration studies. However hourly production cost models tend to dominate the analysis. Hourly studies have some potential drawbacks. Using hourly averages can mask some of the variability in the system. It will also potentially reduce control actions as generation need only be able to respond to changes in an hour. Many studies already include

sub-hourly analysis, but they are typically only for short periods, and have many simplifications which limit the usefulness. Sub-hourly analysis in future studies will need to cover many more possible conditions, as well as be a closer mirror to operations.

Sub-hourly studies can be used to analyze many of the suggestions for practices to integrate wind. Sub-hourly studies are necessary to determine the optimal policies and practices to integrate wind. Sub-hourly studies are often very simplified and lack the detail to make firm recommendations, future sub-hourly studies will need to be more detailed.

### **6.2.2 Extreme Conditions**

Another area that studies often suggest future work is the extreme weather events. Wind studies consider typical operating conditions and historical years, if weather patterns didn't exist in the input data they won't be considered in the study even though they may be possible. There are extreme scenarios which could pose problems to the operation of the grid. Studying those cases could determine strategies to successfully handle them if they occur. Sub hourly studies are often necessary to fully consider extreme events or other areas of concern. Extreme events can be based not only on the wind generation behavior, but also on the simultaneous behavior of the power system.

Along with the studies of possible extreme events studies need to be done on how to mitigate them. Extreme events may require special attention and solutions that are not typically used.

### **6.2.3 Costs and Benefits**

While wind integration costs are the primary focus of some studies, they are not present in others. Future studies to find integration costs are suggested by studies that do not include costs. Other studies may include integration costs but also recommend future studies on costs due to possible changes in the regulatory environment such as emissions controls. Cost studies can also be desired if certain costs were excluded, or not modeled in sufficient detail. For example if studies assumed that wind generation would not affect the price of energy. The other side of cost studies is benefits. Studies often recommend analyzing the benefits of some of the operational changes they suggest implementing. For example quantifying the effects of wind forecasts or curtailment could be important to implementing them.

### **6.2.4 Transmission**

Transmission studies are often neglected or extremely simplified for current wind integration studies. Detailed transmission studies are necessary for before each additional wind plant is installed. Transmission elements must be designed specifically for wind generation to ensure reliability. This would entail an AC transmission analysis as opposed to the DC analysis which is common to most integration studies. The AC analysis would likely focus on the possible electrical issues such as: inertial response, reactive power support, and transient stability.

Another important aspect of a transmission study is a land use study. This study is necessary to ensure that proposed transmission can be built. It would need to consider the arrangement of wind projects to ensure that transmission is appropriately sized and that the connections to the system are made in the most optimal way.

### 6.2.5 Import and Export Studies

Integration studies for the most part are performed by individual balancing areas. The EWITS and WWSIS studies are exceptions they are studies broader in scope covering several balancing areas at once. Balancing areas often have strong ties within their interconnection with significant trades with their neighbors. Balancing areas may be net importers or exporters or pass energy through. The current level of exchange could change when significant wind generation capacity is installed either locally or in a neighboring area. If areas that install wind need to radically change their historical import/export schedule there could be problems. Many large generators and transmission lines are built to serve multiple areas. Given the interconnected nature of the power grid combined with different reliability, RPS, and other regulatory frame works the trading of wind energy can be of concern. Studies which can realistically model integration throughout a large interconnected system will be important to determine how to efficiently manage the power system.

### 6.2.6 Regulations

Emissions regulations are something that is already considered in many studies. However, the actual regulations that will be imposed are unknown and their impact on the power system will need to be studied. The two probably mechanisms for emissions regulations are carbon prices and cap and trade. These two approaches are likely to have very different outcomes in terms of operating the power grid. Modeling the grid with the different options can help policy makers make informed decisions and grid operators plan for the changing procedures.

There are other environmental regulations that will affect the power grid. Water use restrictions are one such example. Some thermal generators use a large amount of water for cooling, and the water is released by into the environment much warmer than it was taken. Regulations to limit these effects could force some generators to shut down which will change the system and studies that do not anticipate these changes will have unrealistic assumptions. This is of concern in California with thermal generation which uses once through cooling. The future operation of many generators within California is in question and the resulting changes will need to be understood.

### 6.2.7 Technology

There are a variety of new technologies being developed today that can help operate the grid much more efficiently. Collectively these technologies are known as smart grid and they can provide lots of benefits. Smart grid technologies will change the characteristics of the power system and the way it is operated. Smart grid can enable loads to be more responsive to prices. Smart grids can also use real time telemetry of system conditions to constantly update transmission constraints allowing more power to flow on the same network. Some technology can even direct the flow of electricity on the power grid. Distributed generation is another possibility for the power grid. All of these new technologies will change the operations in some way. It will be important for operators to study their impacts in conjunction with wind generation.

Storage technology is one area suggested for future study. Storage is often suggested as a way to mitigate wind generation impacts to the power system. Storage technology is rapidly changing. Pumped storage hydro is the most familiar and common in the power system and is well understood. There are many newer storage technologies that are being developed all of which have different characteristics. Energy storage using batteries, flywheels, compressed air, and molten salt have all been suggested. These technologies will need to be examined to see what benefits they can provide to the power system. In addition to understanding the storage technology possible revenue models must be explored.

The expected growth of electric vehicles is another aspect to study in relation to wind generation. Electric vehicles are expected to charge at night when demand is low. This could prove beneficial for wind generation because wind generation in many areas will be at its peak at night. It seems as though electric vehicles will be able to absorb wind energy that won't otherwise be needed. There are several concerns with how this will work in practice. Such as, what happens if the wind dies? Also, will electric vehicles start charging all at the same time leading to a sudden load spike? Is there a way for the chargers to be responsive to the power grid?

## CHAPTER 7:

# Conclusions

This study surveyed the literature on integrating wind power in the power grid from recent years. It focuses on studies released between 2007 and 2010 within the United States. This report describes the operation of the power system. It also gives the characteristics of wind generation. Wind generation is an intermittent, variable and uncertain generating resource. This uncertainty is an important characteristic in that it is in contrast to conventional generation which is available as needed and controllable. System operators worry that these characteristics of wind generation will present control problems in the system. Current wind integration studies focus on the operation of the power system with wind generation. These studies examine the changes that the system will experience and offer alternatives for mitigating the associated risk.

### 7.1 Methodologies

The current wind integration studies focus on the operation of the power system with increasing wind generation. Wind integration studies focus on the operational issues with wind generation and the physical connections are handled in less detail. Wind integration studies perform a variety of analysis to both understand the wind generation on its own and the wind and power grid together. The methodologies that studies use to analyze the wind play an important role in the results. There are a few common methodologies that are employed in many studies, but even with these common tools there are a number of assumptions and parameters which will influence the results. Understanding the differences between two methodologies is very important when trying to compare results between studies.

The system that is studied is one of the driving factors for methodologies and results. Wind integration studies need to define the conditions they are studying. The studies are informed by the current amounts of wind generation on the system but they study future time periods with increased generation. Wind integration studies create different scenarios for how the power system will look in the future, often times with differing amounts of wind generation. It is also common for studies to consider cases with similar amounts of wind generation but spread out into different areas. The underlying assumptions of the system being modeled will affect the methodology that is applied to the system as well as the final results.

Statistical analysis is often the first set of analysis of a wind integration study. The statistical methods tend to study the wind generation profile or the load minus the wind generation profile. In both cases studies analyze the data to determine the magnitude, frequency, and duration of changes. This will define a new baseline of the power system to understand how much the control will change. Statistical methods are also good for understanding the behavior of wind generation by time of day, season, and other factors that are relevant to operation.

Operational analyses are also performed to investigate possible operating changes with increased wind energy. Operational studies will attempt to model the system operations of the

region being studied. This is one area that leads to divergence amongst the models, because there are different operating practices to take into account. The most common type of operational analysis involves using a production cost simulation model on the scenarios. Production cost models simulate the operation of the power grid by matching supply and demand and calculating power flows across the network. Even though the techniques are similar there are many parameters which can differ and affect the results.

## **7.2 Results**

The results of integration studies come in a variety of forms. Results format will be determined by the methodologies chosen and the original goals of the integration study. There are many parameters and assumptions that can influence the results. Direct comparison of results can be misleading due to all the various factors that can influence results. The results can vary widely between the studies and it is important to understand the fundamental differences that lead to different results.

The variability that wind introduces in power systems is generally less than the variability that is present due to load. That does not mean that the wind does not add additional variability. The net load, or load minus wind generation is what system operators will need to accommodate. The variability of the net load is less than the variability of the load plus the variability of the wind. The increase in variability will require system operators to take more and larger control actions to keep the system balanced. The uncertainty of wind in the power system is the largest concern. The variability introduced is generally manageable but it is made much worse by the uncertainty. Uncertainty will lead to less efficient operation and can lead to reliability problems.

The variability and uncertainty of wind generation will cause operators to increase the amount of ancillary services they procure to keep the system balanced. The regulation reserve is the most affected because it is primarily charged with managed short term fluctuations. The amount of additional regulation that systems will need to procure varies greatly between studies. Regulation needs increase with higher penetrations of wind generation. It is important for system operators to quantify the regulation needs to ensure the system will have the capability to provide it.

Determining the costs of wind integration is one of the main goals of many studies. The studies that consider costs have a wide range of methodologies and assumptions they use to determine the costs. There are many possible ways that wind generation can impact the power system costs. It can affect the energy costs, ancillary service costs, unit commitment costs, congestion costs, uplift costs, transmission costs, and so forth. Direct comparison of the wind integration costs from different studies is difficult because studies choose to include different factors. Studies find wind can reduce energy cost by displacing more expensive generation. The savings from energy may be offset by higher costs from higher costs extra such as increased ancillary service costs.

Wind generation can play an important role in helping to reduce emissions from electric power generation. Large amounts of wind power will displace electricity normally produced from

fossil fuel fired generators. Wind generation combined with a carbon tax can results in substantial reduction in emissions. Studies have shown that carbon dioxide reductions can be as large as 45 percent under certain conditions.

### **7.3 Recommendations**

The most important conclusion that is universal among wind integration studies is that reliable operation of the power grid will be possible. The fact that reliable operation will be possible suggests that wind energy will be able to play an important role in meeting future energy needs. Managing the increased wind generation will require many changes to current operating procedures. The success of wind generation could rely on the policies and practices of the system operators. Studies recommend many ways to successfully integrate wind power into the system. The recommendations fall into three basic categories; reducing uncertainty, increasing flexibility, and increasing diversity.

Reducing uncertainty of wind generation is the primary method that is recommended to ease integration. Forecasting for wind generation is the most important strategy to integrate wind into the power grid. It reduces the uncertainty of wind and has potentially very large savings for the power system. The forecasts will be designed for each area to fit with their current operating practices. Forecasts will give foresight into the expected level of generation and variability that wind power will introduce into the system giving operators a chance to make adjustments or procure extra capacity if needed.

Increasing the flexibility of the power grid is the second strategy for managing wind integration. Increasing the amount of ancillary services, specifically regulation, is a common tactic to increase the systems flexibility. This will literally increase the amount of capacity that is tasked with following variations between the load and generation. Other methods of increasing flexibility are also suggested but are more dependent on the system and operating practices.

The third strategy for managing integration is increasing diversity. Diversity can be increased in a number of ways. Building wind generation in different resource areas is one way to increase diversity. Constructing sufficient transmission to ensure wind power can be moved where it is needed is another. Combining control areas is another or increasing the cooperation between areas. Increasing cooperation would involve increased scheduling frequency across interties and sharing of renewable energy data.

Adopting these recommendations will be necessary to ensure that wind power is successfully integrated. Further study of wind power integration will be important as more capacity is installed, as better information becomes available, and as better tools to analyze wind are developed. Wind integration studies are also targeted to address certain goals. There can be many things of interest that fall outside of those goals and must be analyzed in further studies. Studies suggest looking at integration in more detail using sub hourly studies, or extreme weather condition studies. Studies also recommend looking at wind integration with different future conditions that may be driven by development of new technology, environmental regulation, and operating practice changes.

## **GLOSSARY**

Alternating Current (AC) – The common form of electric delivery in which the current is a wave that periodically reverse itself. Alternating current makes up the vast majority of the power grid.

Area Control Error (ACE) – The instantaneous difference between a control areas scheduled interchange and the actual interchange taking into account frequency deviations.

Automatic Generator Control (AGC) — A control algorithm which controls generators on regulation by increasing or decreasing their output every few seconds to adjust to changing load.

Ancillary Service (A/S) – A group of reliability related services which provide the system with control and stabilization functions.

Balancing Area- An area of the power grid with metered boundaries under the control of a balancing authority.

Contingency – The unexpected loss of a system component.

Contingency Reserve – The provision of capacity maintained to restore balance after a contingency event.

Control Performance Standards (CPS1 and CPS2) – Reliability standards that set limits for a balancing areas ACE over time.

CREZ – Competitive Renewable Energy Zone

Curtailment – Shutting down or limiting generation from producing energy that it otherwise would.

Dispatch – The operating instructions which tell generators how much power to produce.

Direct Current (DC) – The unidirectional flow of electricity. It is used for very long high voltage line on the power grid. Direct current is a very common simplification to use when modeling the power grid.

Doubly-fed Induction Generator (DFIG) – A form of electrical generator used in modern wind turbines which has enhanced capabilities over a standard induction generator.

Eastern Wind Integration and Transmission Study (EWITS) – A wind integration study covering the eastern interconnection.

Electric Reliability Council of Texas (ERCOT) – The system operator for the Texas interconnection.

Extra High Voltage (EHV) – Voltages above 500kV, used for high capacity transmission lines.

Federal Energy Regulatory Commission (FERC) – A federal government agency that regulates interstate transmission of electricity, oil, and natural gas.

Frequency – The number of times the current reverses itself per unit time. The electrical grid in the United States operates at 60 Hz.

Independent System Operator (ISO) – An organization that controls and monitors the operation of the electric power system for a balancing area, usually a single state.

Induction Generator (IG) – A form of electrical generator used in older wind turbines. Induction generators require electricity from the power grid to make a magnetic field to generate electricity.

Interconnection – A wide area synchronous grid. Describes an area of the power grid which operates at a synchronized frequency and is electrically tied together.

Kilovolt (kV) – A measure of the basic electromotive force that causes current to flow.

Kilowatt (kW) – A standard unit of electrical power.

Kilowatt Hour (kWh) – A unit of energy equal to one kilowatt of energy consumed for one hour.

LMP – Locational Marginal Price – represents the price of the next unit of power at a distinct element of the power grid.

LVRT – Low Voltage Ride Through

Megawatts (MW) – A unit of power commonly used for power systems equal to 1000 kW.

Megawatt Hour (MWh) – A unit of energy commonly used for power systems.

North American Electric Reliability Corporation (NERC) – An independent company responsible for reliability standards throughout the interconnected North American electric grid.

Non Spinning Reserve – A type of ancillary service made up of generation which can synch to the grid within 10 minutes, or load which can reduce its demand in 10 minutes to restore balance after a contingency.

Numerical Weather Prediction (NWP) – Mathematical models of the physical dynamics of the atmosphere and oceans used to predict the weather.

Operating Reserve – The capability above the system above the load to provide regulation, load following, and for scheduled or forced outages that is not reserved for contingency reserve.

Power – The rate of production or consumption of energy.

Power system – A common term to describe an electricity production, transmission, and distribution system.

Production Cost Models – Models of power system operations which match generation and load respecting a transmission model on a least cost basis.

PTC – Production Tax Credit

QSS – Quasi Steady State

Regional Transmission Organization (RTO) – Similar to an ISO it is an organization that is responsible for controlling and monitoring the electric power system. An RTO's territory is normally larger than an ISO's territory usually covering several states.

Regulation – an amount of reserve controlled by AGC to maintain short term balance of the grid.

RPS – Renewable Portfolio Standards

SCADA – supervisory Control and Data Acquisition System(s)

Spinning Reserve – Synchronized unloaded generation that is ready to be deployed within 10 minutes usually to deal with a contingency event.

Unit Commitment – The process of selecting generators to operate. This process must be done in advance to give sufficient time for generators to turn on and synchronize with the power grid.

Western Electricity Coordinating Council (WECC) – The regional reliability organization for the western interconnection.

Western Wind and Solar Integration Study (WWSIS) – A study of wind integration in several balancing areas of the western interconnection.

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